U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-282 211

Water Recycle/Reuse Alternatives in Coal-Fired Steam-Electric Power Plants: Volume I. Plant Studies and General Implementation Plans

Radian Corp, Austin, Texas

Prepared for

Industrial Environmental Research Lab., Research Triangle Park, N.C.

Mar 78

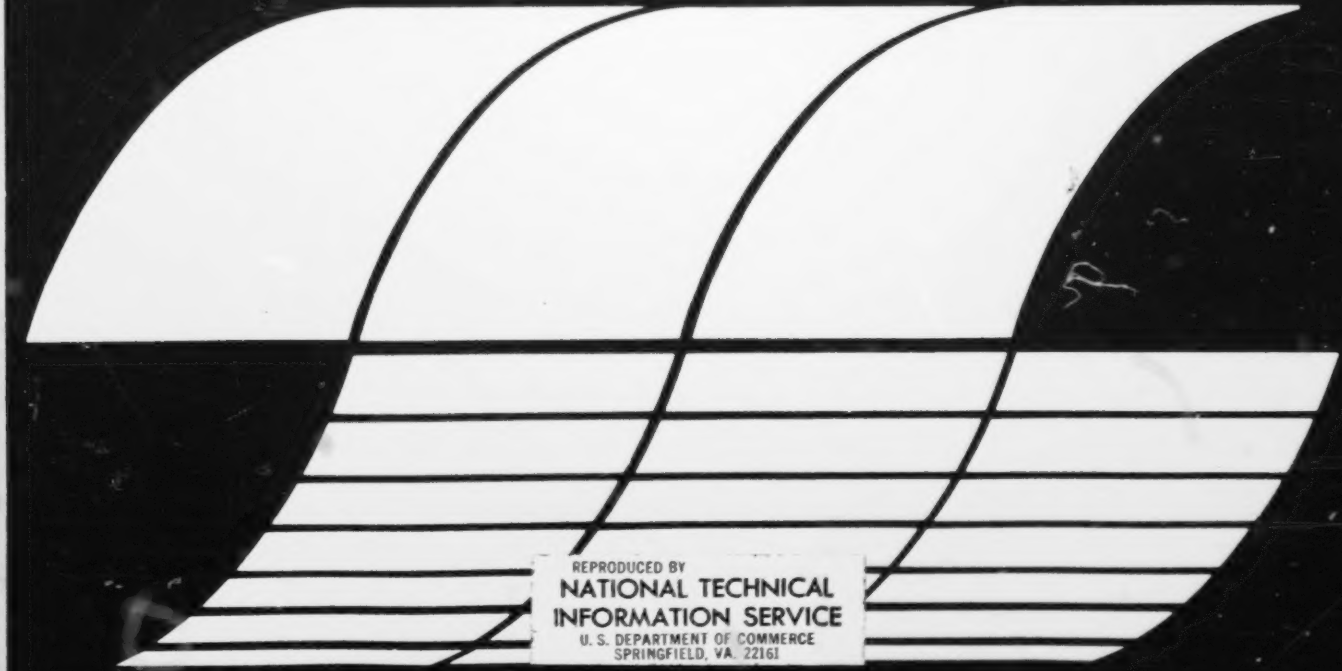
PB 282 211

EPA
U.S Environmental Protection Agency
Office of Research and Development
Industrial Environmental Research
Laboratory
Research Triangle Park, North Carolina 27711
EPA-600/7-78-055a
March 1978

WATER RECYCLE/REUSE ALTERNATIVES IN COAL-FIRED STEAM-ELECTRIC POWER PLANTS:

Volume I. Plant Studies and General Implementation Plans

Interagency
Energy-Environment
Research and Development
Program Report



REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE
U. S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-78-055a	2.	3. RECIPIENT'S ACCESSION NO. PB282211
4. TITLE AND SUBTITLE Water Recycle/Reuse Alternatives in Coal-fired Steam-electric Power Plants: Volume I. Plant Studies and General Implementation Plans		5. REPORT DATE March 1978
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) James G. Noblett and Peter G. Christman		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Radian Corporation P.O. Box 9948 Austin, Texas 78766		10. PROGRAM ELEMENT NO. EHE624
		11. CONTRACT/GRANT NO. 68-03-2339
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development Industrial Environmental Research Laboratory Research Triangle Park, NC 27711		13. TYPE OF REPORT AND PERIOD COVERED Final; 6/75-2/78
		14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES IERL-RTP project officer is Frederick A. Roberts, EPA/ERC, 200 S. 35th St., Corvallis, OR 97330 (503/420-4715).

16. ABSTRACT The report gives results of an investigation of water recycle/treatment/reuse alternatives in coal-fired power plants. Five power plants from representative U.S. regions were studied. The major water systems encountered were cooling, ash sluicing, and SO2/particulate scrubbers. Results were used to provide general implementation plans for the various options identified. Computer models were used to identify the degree of recirculation achievable in each water system without forming scale. The effects of makeup water quality and various operating parameters were determined for each water system. Several alternatives for minimizing water requirements and discharges were studied for each plant, and rough cost estimates were made for comparison. An implementation plan is presented for each water system and is divided into phases, including system characterization, alternative evaluation, pilot studies, and full-scale implementation. This volume discusses the recycle/treatment/reuse opportunities for cooling, ash sluicing, and SO2/particulate scrubbing systems as well as combined systems. It also includes the implementation plans.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Combustion	Pollution Control	13B	21B
Water Treatment	Cooling Water	Stationary Sources		13A
Filtration	Scrubbers	Water Recycle/Reuse	07D	07A
Circulation	Sulfur Oxides	Ash Sluicing		07B
Electric Power Plants	Dust	Particulate	10B	11G
Coal	Mathematical Model		21D	12A

18. DISTRIBUTION STATEMENT Unlimited	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES 138
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE A07 - A01

EPA Form 2220-1 (9-73)

EPA-600/7-78-055a
March 1978

WATER RECYCLE/REUSE ALTERNATIVES IN COAL-FIRED STEAM-ELECTRIC POWER PLANTS:

Volume I. Plant Studies and General Implementation Plans

by

James G. Noblett and Peter G. Christman

Radian Corporation
P.O. Box 9948
Austin, Texas 78766

Contract No. 68-03-2339
Program Element No. EHE624

EPA Project Officer: Frederick A. Roberts

Industrial Environmental Research Laboratory
Office of Energy, Minerals and Industry
Research Triangle Park, N.C. 27711

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, D.C. 20460

ABSTRACT

This study was conducted under EPA Contract No. 68-03-2339 to investigate water recycle/reuse alternatives in coal-fired power plants. In the first part of this program, five typical plants from representative geographical regions of the United States were studied. The major types of water systems encountered at these plants were cooling towers, ash sluicing, and SO_2/particulate scrubbing.

Computer models were used to identify the degree of recirculation achievable in each of these water systems without forming scale. The effects of makeup water quality and various operating parameters were determined for each water system using the models. Several alternatives for minimizing water requirements and discharges were studied for each plant and rough cost estimates were made to compare alternatives.

In the second part of the program generalized implementation plans for the options identified in the plant studies are presented. An implementation plan is presented for each major water system (cooling towers, ash sluicing, scrubbing) where the plans are divided into phases. The phases include system characterization, alternative evaluation, pilot studies, and full-scale implementation. The characterization phase for each system includes discussions of the important process variables to consider when modifying the system. The alternative evaluation phase descriptions include discussions of various recycle/reuse alternatives and present methodologies for evaluating the feasibility of those options. The pilot studies and full-scale implementation discussions include descriptions of equipment required and important operating variables to be considered.

The overall report is presented in two volumes. The first volume discusses the recycle/reuse opportunities for cooling tower, ash sluicing, and SO_2/particulate scrubbing systems, as well as for combined systems. The first volume also contains the results of the studies to prepare generalized implementation plans. Volume II presents the detailed studies for each plant, the selection methodology, the results of the laboratory studies for ash sluicing, the results of kinetic studies for $CaCO_3$ and $Mg(OH)_2$, and a description of the models used in this study.

VOLUME I
CONTENTS

PAGE

ABSTRACT -- iii
CONTENTS, VOLUME I ---------------------------- iv
CONTENTS, VOLUME II --------------------------- viii
FIGURES, VOLUME I ----------------------------- xxii
TABLES, VOLUME I -------------------------------xxiii
ACKNOWLEDGEMENT ------------------------------- xv

PLANT STUDIES

1.0 INTRODUCTION ---------------------------------- 1
  1.1 Program Objectives ------------------------ 1
  1.2 Summary ----------------------------------- 1
  1.3 Conclusions and Recommendations ----------- 4
2.0 COOLING SYSTEMS ------------------------------- 7
  2.1 Process Description ----------------------- 8
  2.2 Process Variables ------------------------- 13
    2.2.1 Cycles of Concentration ------------- 13
    2.2.2 Relative Saturation ----------------- 14
  2.3 Treatment Options ------------------------- 15
    2.3.1 Acid Treatment ---------------------- 16
    2.3.2 Calcium Removal --------------------- 18
  2.4 Recycle/Reuse Alternatives in Cooling Towers ---------------------------------- 26
3.0 ASH SLUICING SYSTEMS -------------------------- 30
  3.1 Process Description ----------------------- 30
  3.2 Process Variables ------------------------- 33
    3.2.1 Ash Reactivity ---------------------- 34

Preceding page blank

VOLUME I
CONTENTS
(Continued)

PAGE

3.2.2 Makeup Water Quality -------------- 36
3.2.3 Carbon Dioxide Transfer ----------- 40
3.2.4 Degree of Recycle ----------------- 44
3.3 Recycle/Reuse Alternatives in Ash Sluicing Systems ---------------------------------- 44
4.0 SO_2/PARTICULATE SCRUBBING SYSTEMS ------------- 47
4.1 Process Description --------------------- 47
4.1.1 Gas Cleaning ---------------------- 49
4.1.2 Solids Precipitation -------------- 49
4.1.3 Solid/Liquid Separation ----------- 50
4.2 Process Variables ----------------------- 51
4.2.1 SO_2 Removal Rate ------------------ 52
4.2.2 Ash Removal Rate ------------------ 54
4.2.3 Ash Pond Recycle Rate ------------- 58
4.2.4 Slurry Solids Concentration ------- 58
4.2.5 Reaction Tank Size ---------------- 61
4.2.6 Liquid-to-Gas Ratio --------------- 63
4.2.7 Makeup Water Quality -------------- 66
4.3 Recycle/Reuse Alternatives in SO_2/ Particulate Scrubbing Systems ----------- 68
5.0 COMBINED SYSTEMS ---------------------------- 70
5.1 APS Four Corners ------------------------ 70
5.2 PSC Comanche ---------------------------- 73
5.3 GPC Bowen ------------------------------- 76
5.4 PP&L Montour ---------------------------- 79
5.5 MPC Colstrip ---------------------------- 81
5.6 Recycle/Reuse Alternatives in Combined Systems --------------------------------- 83

VOLUME I

CONTENTS

(Continued)

PAGE

GENERALIZED IMPLEMENTATION PLANS

1.0 INTRODUCTION ---------------------------------- 87

2.0 COOLING TOWERS ---------------------------------- 89

2.1 Phase I: Cooling Tower Characterization --- 92

2.1.1 Identification of Process Variables - 92

2.1.2 Sampling Program -------------------- 96

2.2 Phase II: Evaluation of Operating Alternatives -------------------------------- 97

2.2.1 Evaluation Criteria ----------------- 98

2.2.1.1 Scale Potential ------------ 98

2.2.1.2 Treatment Alternatives ----- 100

2.2.2 Model Application ------------------- 103

2.3 Phase III: Cooling Tower Modifications ---- 105

2.3.1 Equipment --------------------------- 105

2.3.2 Implementation ---------------------- 106

3.0 ASH SLUICING ---------------------------------- 110

3.1 Phase I: Ash System Characterization ------ 112

3.1.1 Identification of Process Variables - 112

3.1.2 Sampling ---------------------------- 114

3.1.3 Laboratory Studies ------------------ 114

3.2 Phase II: Evaluation of Operating Alternatives -------------------------------- 117

3.2.1 Evaluation Criteria ----------------- 118

3.2.1.1 Scale Potential ------------ 119

3.2.1.2 Treatment Alternatives ----- 119

3.2.2 Model Application ------------------- 121

3.3 Phase III: Ash Sluicing Pilot Studies ----- 122

3.4 Phase IV: Full-Scale Implementation ------- 126

3.4.1 Equipment --------------------------- 126

3.4.2 Implementation ---------------------- 127

VOLUME I

CONTENTS

(Continued)

PAGE

4.0 SO_2/ PARTICULATE SCRUBBING ---------------------- 128
4.1 Phase I: System Characterization ---------- 130
4.1.1 Identification of Process Variables - 130
4.1.1.1 Scrubber and Demister Data - 131
4.1.1.2 Reaction Tank Data --------- 135
4.1.1.3 Solids Concentration Data -- 137
4.1.2 Sampling Plan ---------------------- 137
4.1.2.1 Analytical Measurements ---- 139
4.1.2.2 Process Measurements ------- 142
4.2 Phase II: Alternative Evaluation ---------- 145
4.2.1 Evaluation Criteria ---------------- 145
4.2.1.1 Scale Potential ------------ 146
4.2.1.2 Dissolved Solids Concentration -------------- 148
4.2.2 Model Application ------------------ 148
4.3 Phase III: Pilot-Scale Studies ------------ 150
4.3.1 Converting to Closed-Loop Operation - 150
4.3.2 Changing Makeup Water Source -------- 152
4.4 Phase IV: Full-Scale Operations ----------- 153
5.0 SUMMARY --- 154
REFERENCES --- 156

VOLUME II
CONTENTS

PAGE

CONTENTS, VOLUME I ---------- iv
CONTENTS, VOLUME II ---------- viii
FIGURES ---------- xxii
TABLES ---------- xxiii

APPENDIX A - POWER PLANT SELECTION CRITERIA
1.0 INTRODUCTION ---------- A-1
2.0 SELECTION CRITERIA ---------- A-2
3.0 SELECTION METHODOLOGY ---------- A-4
  3.1 Plant Identification ---------- A-4
    3.1.1 Southwest ---------- A-4
    3.1.2 Northern Great Plains ---------- A-6
    3.1.3 Southeast ---------- A-8
    3.1.4 Northeast ---------- A-8
  3.2 Plant Selection ---------- A-11

APPENDIX B - CHEMICAL CHARACTERIZATION OF PLANT WATER SYSTEMS
1.0 INTRODUCTION ---------- B-1
2.0 SAMPLING ---------- B-2
  2.1 Four Corners Generating Station (Arizona Public Service) ---------- B-4
  2.2 Comanche Generating Station (Public Service of Colorado) ---------- B-5
  2.3 Bowen Generating Station (Georgia Power Co.) ---------- B-6
  2.4 Montour SES (Penn. Power & Light) ---------- B-7
  2.5 Colstrip SES (Montana Power Co.) ---------- B-8
3.0 ANALYTICAL TECHNIQUES ---------- B-11
  3.1 Calcium, Magnesium, Sodium, Potassium, and Arsenic ---------- B-11

VOLUME II

CONTENTS

(Continued)

PAGE

3.2 Chloride ---------------------------------- B-11
3.3 Total Sulfur and Sulfate ---------------- B-11
3.4 Carbonate -------------------------------- B-12
3.5 Nitrate ---------------------------------- B-12
3.6 Phosphate -------------------------------- B-12
3.7 Silicate --------------------------------- B-12
3.8 Total Dissolved Solids ------------------ B-12
3.9 Sulfite ---------------------------------- B-12
4.0 RESULTS ---------------------------------- B-14
4.1 Four Corners Generating Station ---------- B-14
4.2 Comanche Generating Station ------------- B-16
4.3 Bowen Generating Station ---------------- B-18
4.4 Montour SES (PP&L) ---------------------- B-18
4.5 Colstrip SES (Montana Power Co.) --------- B-21

APPENDIX C - $CaCO_3$ AND $Mg(OH)_2$ PRECIPITATION KINETICS

1.0 INTRODUCTION ---------------------------- C-1
2.0 LITERATURE SURVEY ----------------------- C-2
2.1 Basis of the Literature Survey ---------- C-2
2.2 Solubility Data ------------------------- C-2
2.2.1 $CaCO_3$ ------------------------------ C-2
2.2.2 $Mg(OH)_2$ ---------------------------- C-4
2.3 Solubility Product Data ----------------- C-5
2.3.1 $CaCO_3$ ------------------------------ C-6
2.3.2 $Mg(OH)_2$ ---------------------------- C-6
2.4 Dissociation and Ion-Pairing Data -------- C-7
2.5 Formation and Kinetic Data -------------- C-7
2.5.1 $CaCO_3$ ------------------------------ C-7
2.5.2 $Mg(OH)_2$ ---------------------------- C-10

VOLUME II
CONTENTS
(Continued)

PAGE

3.0 APPARATUS AND PROCEDURES
  3.1 Description of Experimental Apparatus ---- C-13
    3.1.1 Inlet Feed Systems ---------------- C-13
    3.1.2 Batch-Solid Reactor --------------- C-16
  3.2 Experimental Procedures ----------------- C-16
    3.2.1 Preparation of Feed Solutions ----- C-17
    3.2.2 Preparation of Batch-Solid Crystallizer --------------------- C-17
    3.2.3 Experimental Run Procedure -------- C-18
    3.2.4 Sampling Scheme for Experimental Run Procedure -------------------- C-19
      3.2.4.1 Inlet Feed Solutions ----- C-19
      3.2.4.2 Intermediate Diluted Filtrate Samples --------- C-20
      3.2.4.3 Steady-State Diluted Filtrate Samples --------- C-20
  3.3 Analytical Procedures ------------------- C-20
    3.3.1 Determination of Sodium, Calcium and Magnesium ------------ C-20
    3.3.2 Determination of Chloride --------- C-21
    3.3.3 Determination for Alkalinity ------ C-21
    3.3.4 Determination of Total Carbonate -- C-21
4.0 EXPERIMENTAL RESULTS FOR $CaCO_3$ --------------- C-22
  4.1 Kinetics Data Processing ---------------- C-22
  4.2 Results --------------------------------- C-24
  4.3 Discussion of Results ------------------- C-24
  4.4 Conclusions ----------------------------- C-27
5.0 EXPERIMENTAL RESULTS FOR $Mg(OH)_2$ ------------- C-28
  5.1 Kinetics Data Processing ---------------- C-28
  5.2 Results --------------------------------- C-30

VOLUME II

CONTENTS

(Continued)

PAGE

5.3 Discussion of Results -------------------- C-30
5.4 Conclusions ------------------------------ C-33

APPENDIX D - ASH CHARACTERIZATION FOR COLSTRIP AND MONTOUR FLY ASHES

1.0 INTRODUCTION ----------------------------- D-1
1.1 Background ------------------------------- D-1
1.2 Summary ---------------------------------- D-1
2.0 EXPERIMENTAL ----------------------------- D-3
2.1 Technical Approach ----------------------- D-3
2.2 Montour SES ------------------------------ D-6
2.3 Colstrip SES ----------------------------- D-10
3.0 RESULTS ---------------------------------- D-14
3.1 Montour ---------------------------------- D-14
3.1.1 Steady-State Operation ----------------- D-14
3.1.2 Chemical Analyses ---------------------- D-22
3.1.3 Mass Balances -------------------------- D-23
3.1.4 Conclusions ---------------------------- D-27
3.2 Colstrip --------------------------------- D-27
3.2.1 Chemical Analyses ---------------------- D-27
3.2.2 Mass Balance --------------------------- D-28
3.2.3 Conclusions ---------------------------- D-32

APPENDIX E - COMPUTER MODELS

1.0 INTRODUCTION ----------------------------- E-1
2.0 MODEL DESCRIPTIONS ----------------------- E-2
2.1 Ash Sluicing (Bowen, Montour, Comanche) -- E-3

VOLUME II
CONTENTS
(Continued)

PAGE

2.2 Cooling Tower Model ---------------------- E-5

2.2.1 Hot Side Blowdown at Bowen, Montour and Colstrip ------------- E-5

2.2.2 Cold Side Blowdown at Comanche ---- E-8

2.3 SO_2-Particulate Scrubbing --------------- E-10

2.3.1 SO_2-Particulate Scrubbing at Four Corners ------------------ E-10

2.3.2 SO_2-Particulate Scrubbing at Colstrip ---------------------- E-15

3.0 SUBROUTINE DESCRIPTIONS ---------------------- E-17

3.1 Input Subroutines ---------------------- E-17

3.2 Equipment Subroutines ------------------- E-18

3.3 System Balance Subroutines -------------- E-31

4.0 CHEMICAL EQUILIBRIUM PROGRAM ----------------- E-33

4.1 Chemical Species ----------------------- E-33

4.2 System Equilibria ---------------------- E-35

4.3 Material Balance ----------------------- E-35

4.4 Constants ------------------------------ E-37

4.4.1 Equilibrium Constants ------------ E-37

4.4.2 Activity Coefficients ------------ E-39

4.5 Makeup Water Adjustment ---------------- E-40

APPENDIX F - RECYCLE/REUSE OPTIONS AT FOUR CORNERS (ARIZONA PUBLIC SERVICE)

1.0 INTRODUCTION -------------------------------- F-1

1.1 Summary -------------------------------- F-1

2.0 PLANT CHARACTERISTICS ------------------------ F-4

2.1 Water Balance -------------------------- F-4

2.1.1 Cooling and Bottom Ash Sluicing Systems ----------------- F-10

VOLUME II

CONTENTS

(Continued)

PAGE

2.1.2 Particulate Scrubbing System ----- F-10

2.2 Existing Operations -------------------- F-12

2.2.1 Simulation Basis ---------------- F-12

2.2.2 Simulation Results -------------- F-17

3.0 TECHNICAL ALTERNATIVES ---------------------- F-21

3.1 Alternative One ----------------------- F-22

3.1.1 Simulation Basis ---------------- F-22

3.1.2 Simulation Results -------------- F-24

3.2 Alternative Two ----------------------- F-24

3.2.1 Simulation Basis ---------------- F-24

3.2.2 Simulation Results -------------- F-28

3.3 Alternative Three --------------------- F-31

3.3.1 Simulation Basis ---------------- F-31

3.3.2 Simulation Results -------------- F-31

3.4 Alternative Four ---------------------- F-35

3.4.1 Simulation Basis ---------------- F-35

3.4.2 Simulation Results -------------- F-38

3.5 Conclusions --------------------------- F-38

4.0 ECONOMICS --------------------------------- F-41

APPENDIX G - RECYCLE/REUSE OPTIONS AT BOWEN
(GEORGIA POWER CO.)

1.0 INTRODUCTION ------------------------------ G-1

2.0 PLANT CHARACTERISTICS --------------------- G-5

2.1 Water Balance ------------------------- G-5

2.2 Cooling Tower System ------------------ G-9

2.2.1 Simulation Basis ---------------- G-10

2.2.2 Simulation Results -------------- G-12

VOLUME II

CONTENTS

(Continued)

PAGE

2.3 Ash Handling Systems -------------------- G-16
2.3.1 Simulation Basis ----------------- G-17
2.3.2 Simulation Results --------------- G-20
3.0 TECHNICAL ALTERNATIVES ---------------------- G-22
3.1 Cooling Tower System ------------------- G-22
3.1.1 Simulation Basis ----------------- G-22
3.1.2 Effect of Increased Cycles of Concentration ----------------- G-23
3.1.3 Effect of Calcium Concentration in the Makeup Water --------- G-27
3.1.4 Summary of Cooling Tower Alternatives -------------------- G-33
3.2 Ash Handling Systems ------------------- G-33
3.2.1 Simulation Basis ----------------- G-34
3.2.2 Once-Through Ash Sluicing System ---------------------------- G-34
3.2.3 Recirculating Ash Sluicing System ---------------------------- G-37
3.2.4 Effects of Carbon Dioxide Mass Transfer --------------------- G-40
3.2.5 Effect of $CaSO_4 \cdot 2H_2O$ Supersaturation in the Pond Recycle Water --------------------- G-43
3.2.6 Summary of Ash Sluicing Operations ------------------------ G-44
3.3 Conclusions ------------------------------- G-44
4.0 ECONOMICS -- G-47

APPENDIX H - RECYCLE/REUSE OPTIONS AT COMANCHE
(PUBLIC SERVICE OF COLORADO)

1.0 INTRODUCTION ------------------------------------ H-1

VOLUME II

CONTENTS

(Continued)

PAGE

2.0 PLANT CHARACTERISTICS -------------------------- H-6
  2.1 Overall Water Balance -------------------- H-6
  2.2 Cooling System -------------------------- H-10
    2.2.1 Simulation Basis ------------------ H-11
    2.2.2 Simulation Results ---------------- H-15
  2.3 Ash Disposal System --------------------- H-17
3.0 TECHNICAL ALTERNATIVES ------------------------ H-19
  3.1 Cooling Towers -------------------------- H-19
    3.1.1 Simulation Basis ------------------ H-20
    3.1.2 Effect of Increased Cycles of Concentration ------------------ H-20
    3.1.3 Effect of Sulfate Concentration in the Makeup Water -------------- H-25
  3.2 Ash Handling Systems -------------------- H-25
    3.2.1 Simulation Basis ------------------ H-27
    3.2.2 Once-Through Ash Sluicing System -------------------------- H-29
    3.2.3 Recirculating Ash Sluicing System -------------------------- H-33
    3.2.4 Effect of Carbon Dioxide Mass Transfer -------------------- H-37
  3.3 Conclusions ----------------------------- H-40
4.0 ECONOMICS ------------------------------------- H-42

APPENDIX I - RECYCLE/REUSE OPTIONS AT MONTOUR
(PENNSYLVANIA POWER & LIGHT CO.)

1.0 INTRODUCTION ---------------------------------- I-1
2.0 PLANT CHARACTERISTICS -------------------------- I-5
  2.1 Water Balance --------------------------- I-5
  2.2 Cooling Tower System -------------------- I-9

VOLUME II

CONTENTS
(Continued)

PAGE

2.2.1 Simulation Basis ------------------ I-9
2.2.2 Simulation Results ---------------- I-13
2.3 Ash Handling Systems -------------------- I-15
2.3.1 Simulation Basis ------------------ I-15
2.3.2 Simulation Results ---------------- I-17
3.0 TECHNICAL ALTERNATIVES ------------------------ I-21
3.1 Cooling Tower System -------------------- I-21
3.1.1 Simulation Basis ------------------ I-21
3.1.2 Effect of Increased Cycles of Concentration ------------------ I-22
3.1.3 Effect of Magnesium Concentration in the Makeup Water ------- I-25
3.1.4 Conclusions ----------------------- I-29
3.2 Ash Handling System --------------------- I-29
3.2.1 Simulation Basis ------------------ I-30
3.2.2 Recirculating Ash Systems --------- I-30
3.2.3 Effect of $CaSO_4 \cdot 2H_2O$ Supersaturation in the Pond Recycle Water --------------------- I-33
3.2.4 Effect of Carbon Dioxide Mass Transfer -------------------- I-34
3.2.5 Arsenic Discharges ---------------- I-37
3.2.6 Conclusions ----------------------- I-37
3.3 Summary --------------------------------- I-38
4.0 ECONOMICS ------------------------------------ I-41

APPENDIX J - RECYCLE/REUSE OPTIONS AT COLSTRIP (MONTANA POWER CO.)
1.0 INTRODUCTION --------------------------------- J-1
2.0 PLANT CHARACTERISTICS ------------------------ J-5

VOLUME II

CONTENTS

(Continued)

PAGE

2.1 Water Balance ---------------------------- J-5

2.2 Cooling Tower System -------------------- J-10

2.2.1 Simulation Basis ----------------- J-10

2.2.2 Simulation Results --------------- J-13

2.3 Scrubbing System ------------------------ J-16

2.3.1 Simulation Basis ----------------- J-16

2.3.2 Simulation Results --------------- J-20

3.0 TECHNICAL ALTERNATIVES ---------------------- J-25

3.1 Cooling Tower System -------------------- J-25

3.1.1 Simulation Basis ----------------- J-25

3.1.2 Cooling Tower Makeup Treatment Alternatives ------------ J-26

3.1.3 Effects of Calcium Concentration in Makeup Water at 20 Cycles of Concentration ----------------- J-28

3.1.4 Effect of Sulfate Concentration in Makeup Water at 20 Cycles of Concentration ----------------- J-31

3.1.5 Summary of Cooling Tower Alternatives --------------------- J-31

3.2 Ash Handling (Particulate and SO_2 Scrubbing) System ---------------------- J-35

3.2.1 Simulation Basis ----------------- J-35

3.2.2 Effects of Flue Gas Ash Content --------------------- J-35

3.2.3 Effects of Slurry Solids Content -------------------------- J-37

3.2.4 Effects of Makeup Water Composition --------------------- J-38

3.2.5 Summary of Scrubbing Alternatives -------------------- J-40

3.3 Combined System Alternatives ------------- J-40

VOLUME II

CONTENTS

(Continued)

PAGE

4.0 ECONOMICS ---------------------------------- J-42

APPENDIX K - POWER PLANT DATA REDUCTION

1.0 APS FOUR CORNERS STATION ---------------------- K-1

1.1 Four Corners Scrubbing System ------------ K-1

1.1.1 Four Corners Scrubbing System Particulate Removal Efficiency ------------------------ K-1

1.1.2 Four Corners SO_2 Oxidation Rate -------------------- K-2

1.1.3 Four Corners Flue Gas Composition Calculations ---------- K-2

1.1.4 Batch Dissolution Results with Fly Ash From Four Corners ---- K-5

2.0 GPC PLANT BOWEN ------------------------------ K-8

2.1 Bowen Cooling Towers --------------------- K-8

2.1.1 Climatological Data --------------- K-8

2.2 Bowen Ash System (Units 3 or 4) ---------- K-10

2.2.1 Fly Ash --------------------------- K-10

2.2.2 Total Ash from All Units ---------- K-10

2.2.3 Recirculating Ash System Flows ---- K-11

2.2.4 Pond Evaporation ------------------ K-11

2.2.5 Ash Dissolution ------------------- K-12

3.0 PSC COMANCHE PLANT --------------------------- K-14

3.1 Comanche Cooling Towers ------------------ K-14

3.1.1 Inlet Air Composition ------------- K-14

3.2 Comanche Ash System ---------------------- K-15

3.2.1 Ash Flows ------------------------- K-15

3.2.2 Pond Evaporation ------------------ K-16

3.2.3 Ash Dissolution ------------------- K-17

VOLUME II
CONTENTS
(Continued)

PAGE

4.0 PP&L MONTOUR ---------------------------------- K-19
  4.1 Montour Cooling Towers -------------------- K-19
    4.1.1 Montour Climatological Data -------- K-19
    4.1.2 Montour Heat Load ------------------ K-21
    4.1.3 Montour ACB Index ------------------ K-23
  4.2 Montour Ash System ----------------------- K-24
    4.2.1 Montour Fly Ash -------------------- K-24
    4.2.2 Montour Bottom Ash and Mill Rejects ---------------------- K-25
    4.2.3 Montour Pond Evaporation ----------- K-26
    4.2.4 Montour Calcium Removal Rate ------- K-27
    4.2.5 Montour Ash Dissolution ------------ K-29
      4.2.5.1 Procedure ----------------- K-30
      4.2.5.2 Results ------------------- K-30
5.0 MPC COLSTRIP ---------------------------------- K-34
  5.1 Colstrip Cooling Towers ------------------ K-34
    5.1.1 Colstrip Climatological Data ------- K-34
  5.2 Colstrip Scrubbing System ---------------- K-35
    5.2.1 Colstrip Flue Gas Composition ------ K-36
    5.2.2 Colstrip Effluent Tank Sample Consistency ----------------- K-37
    5.2.3 Colstrip Ash Dissolution ----------- K-39

APPENDIX L - ASH CHARACTERIZATION FOR FOUR CORNERS, BOWEN, AND COMANCHE FLY ASHES

ABSTRACT -- L-1
1.0 INTRODUCTION ---------------------------------- L-2
  1.1 Background -------------------------------- L-2
  1.2 Summary ----------------------------------- L-2

VOLUME II
CONTENTS
(Continued)

PAGE

1.2.1 Carbon Dioxide Sorption ---------- L-2
1.2.2 Closed-Loop Sluicing ------------- L-3
1.2.3 Leaching and Batch Dissolution --- L-4
2.0 CARBON DIOXIDE SORPTION TESTS ---------------- L-5
2.1 Technical Approach ---------------------- L-5
2.2 Experimental ---------------------------- L-5
2.2.1 pH = 11, Nonbuffered Test Medium L-5
2.2.2 pH = 11, Buffered Test Medium ---- L-8
2.2.3 pH = 9, Buffered Test Medium ----- L-8
2.3 Data ------------------------------------ L-8
2.4 Conclusions ----------------------------- L-8
3.0 BENCH-SCALE SLUICING TESTS ------------------ L-12
3.1 Technical Approach ---------------------- L-12
3.2 Experimental ---------------------------- L-15
3.2.1 Comanche Steam-Electric Station -- L-15
3.2.2 Plant Bowen ---------------------- L-16
3.2.3 Four Corners Power Plant --------- L-17
3.3 Results --------------------------------- L-17
3.4 Conclusions ----------------------------- L-17
3.4.1 Comanche Steam-Electric Station -- L-17
3.4.2 Plant Bowen ---------------------- L-25
3.4.3 Four Corners Power Plant --------- L-29
4.0 BATCH DISSOLUTION AND LEACHING TESTS --------- L-31
4.1 Technical Approach ---------------------- L-31
4.1.1 Ash Leaching --------------------- L-31
4.1.2 Batch Dissolution ---------------- L-32
4.2 Experimental ---------------------------- L-33
4.2.1 Ash Leaching --------------------- L-33
4.2.2 Batch Dissolution ---------------- L-33

VOLUME II

CONTENTS

(Continued)

PAGE

4.3 Results ---------------------------------- L-34

4.4 Conclusions ------------------------------ L-34

  4.4.1 Ash Leaching -------------------- L-34

  4.4.2 Comanche Steam-Electric Station -- L-34

    4.4.1.2 Plant Bowen ------------- L-38

    4.4.1.3 Four Corners Power Plant L-40

  4.4.2 Batch Dissolutions --------------- L-44

    4.4.2.1 Comanche Steam-Electric Station ----------------- L-44

    4.4.2.2 Plant Bowen ------------- L-46

    4.4.2.3 Four Corners Power Plant L-46

APPENDIX LA - TEST PARAMETERS AND CHEMICAL ANALYSES FOR CLOSED-LOOP SLUICING TESTS -------- L-47

APPENDIX LB - CORRELATION PARMETERS FOR CLOSED-LOOP SLUICING TESTS ------------------------ L-60

APPENDIX LC - pH AND EMF VALUES OF CALCIUM AND DIVALENT CATION SPECIFIC ELECTRODES FOR BATCH DISSOLUTION TESTS ----------- L-68

VOLUME I

FIGURES

PAGE

PLANT STUDIES

Figure 2-1. General cooling tower system flow scheme. ------ 9

Figure 2-2. Calculated acid requirements as a function of cycles of concentration. ---------------------- 19

Figure 2-3. Gypsum relative saturation variation with cycles of concentration. ---------------------- 22

Figure 2-4. Solution deviations from ideality with cycles of concentration. ---------------------------- 23

Figure 2-5. Slipstream rate as a function of makeup calcium concentration at Colstrip. -------------------- 27

Figure 2-6. Slipstream rate as a function of makeup sulfate concentration at Colstrip. -------------------- 28

Figure 3-1. Typical once-through ash sluicing flow scheme. - 32

Figure 3-2. Recirculating ash sluicing flow scheme. -------- 32

Figure 3-3. Reactive calcium in fly ashes as a function of pH. --- 37

Figure 3-4. Reactive sulfate in fly ashes as a function of pH. --- 38

Figure 4-1. Typical scrubbing system flow scheme. ---------- 48

GENERALIZED IMPLEMENTATION PLANS

Figure 2-1. General cooling tower system flow scheme. ------ 90

Figure 2-2. $CaCO_3$ scale potential as a function of cycles of concentration in cooling towers without treatment (example). --------------------------------- 101

Figure 2-3. Cooling tower blowdown pH as a function of cycles of concentration in towers without treatment (example). ------------------------- 102

Figure 3-1. Recirculating ash sluicing flow scheme. ------- 111

Figure 3-2. Bench-scale model of ash sluicing facilities. - 116

Figure 3-3. General pilot scale ash sluicing facility. ---- 123

Figure 4-1. Typical scrubbing system flow scheme. --------- 132

Figure 4-2. Sample points for scrubbing system characterization. ---------------------------------- 140

VOLUME I
TABLES

PAGE

PLANT STUDIES

Table 1-1. Selected Plants for Water Recycle/Reuse Study -- 2
Table 2-1. Cooling Tower System Design Parameters --------- 10
Table 2-2. Normalized Cooling Tower Design Parameters ----- 12
Table 2-3. Effects of Slipstream Softening on Treatment Rate at Colstrip ------------------------------ 25
Table 3-1. Ash Reactivity Determined from Leaching Studies -- 35
Table 3-2. Effects of Makeup Water Quality on Recirculating Ash Sluice System Scaling Potential ------------ 39
Table 3-3. Effects of Makeup Water Quality on Treatment Required for Closed-Loop Ash Sluicing of Montour Ash ------------------------------------ 41
Table 3-4. Effects of CO_2 Transfer in Pond on Fly Ash Slurry Scaling Tendency (Bench-Scale Results) -- 42
Table 3-5. Effects of CO_2 Transfer in Pond on Fly Ash Slurry Scaling Tendency (Computer Model Results) --------------------------------------- 43
Table 3-6. Effects of Degree of Recycle in an Ash Sluicing System Using Montour Ash ---------------------- 45
Table 4-1. Effects of SO_2 Removal Rate on Four Corners Scrubber Makeup Requirements ------------------ 53
Table 4-2. Effects of Ash Removal Rate on Scrubber Makeup Requirements ---------------------------------- 56
Table 4-3. Effect of Ash Removal Rate on Colstrip Scrubbing System Scaling Tendency ----------------------- 57
Table 4-4. Effect of Pond Recycle on Four Corners Scrubber Makeup Requirements --------------------------- 59
Table 4-5. Effect of Ash Pond Recycle on Four Corners Scrubbing System Scaling Tendency ------------- 60
Table 4-6. Effect of Slurry Solids Concentration on Colstrip Scrubber Scale Potential ---------------------- 62
Table 4-7. Effect of Reaction Tank Volume on Four Corners Scrubbing System Scaling Potential ------------ 64
Table 4-8. Effects of Liquid-to-Gas Ratio on Four Corners Scrubbing Operation -------------------------- 65

VOLUME I

TABLES

(Continued)

PAGE

Table 4-9. Effects of Makeup Water Quality on Colstrip Scrubbing System Scaling Potential ------------ 67

Table 5-1. Summary of Recycle/Reuse Options at Four Corners -- 72

Table 5-2. Summary of Water Recycle/Reuse Options at Comanche -- 74

Table 5-3. Summary of Technically Feasible Options at Bowen -- 77

Table 5-4. Summary of Technically Feasible Options at Montour -- 80

Table 5-5. Summary of Water Recycle/Reuse Options at Colstrip -- 82

GENERALIZED IMPLEMENTATION PLANS

Table 2-1. General Data Sheet for Cooling Towers --------- 93

Table 4-1. Scrubber and Demister Data -------------------- 133

Table 4-2. Reaction Tank Data ---------------------------- 136

Table 4-3. Solids Concentration Data --------------------- 138

Table 4-4. Scrubbing System Characterization Measurements Sample Points and Analyses -------------------- 141

Table 4-5. Process Data Requirements --------------------- 143

ACKNOWLEDGEMENT

This study was conducted by Radian Corporation, Austin, Texas, for EPA under Contract No. 68-03-2339. Mr. Fred A. Roberts of the Corvallis Environmental Research Laboratory was the EPA Project Officer. The Radian program staff included Dr. Frank G. Mesich as Program Manager and Dr. Delbert M. Ottmers as Technical Project Director for the first year. Mr. James G. Noblett served as Technical Project Director for the completion of the project.

The final report was prepared by Mr. James G. Noblett and Mr. Peter G. Christman with Dr. Delbert M. Ottmers providing review. Drs. Ron E. Pyle and Frank B. Meserole coordinated the precipitation kinetics work. Dr. Frank B. Meserole also coordinated the sampling and analyses efforts, and the ash characterization studies. Mr. Michael Fuchs and Mr. Michael Ellsworth were primary contributors to the ash characterization studies.

Mr. Wayne A. Gathman was the primary contributor to the studies at Comanche and Mr. O. W. Hargrove was a primary contributor to the Four Corners studies. The remaining plant studies were conducted by Mr. James G. Noblett and Mr. Peter G. Christman.

Acknowledgement is also given to the personnel from Georgia Power Co., Arizona Public Service Co., Public Services of Colorado Co., Montana Power Co., Pennsylvania Power and Light Co., and Southern Services, Inc. whose cooperation greatly facilitated this work.

PLANT STUDIES

1.0 INTRODUCTION

Achievement of the national goal of "zero-discharge" of pollutants to the environment will necessitate that industrial water users consider possibilities for recycle or reuse of wastewater streams. Electric power plants may presently incorporate some recycle/reuse of wastewater for expediency or short-term economy, but limited availability and rising costs of water, together with water treatment requirements has placed an increased importance on recycle/reuse.

1.1 Program Objectives

The overall objectives of this project are to provide general technical and economic evaluations of water recycle/reuse and treatment options for coal-fired power plants through the use of computer process models.

The primary objective is to make a reliable technical assessment of various recycle/reuse alternatives for five regionally representative power plants chosen for study. This includes determining the system sensitivity to operating parameters which are subject to variations.

A second objective is to prepare rough cost estimates for the purpose of complementing the technical assessment in determining the most attractive options for each plant situation encountered. These rough cost estimates are for comparative purposes and are based on nominal sizing of process and treatment equipment. Rough cost estimates are included for capital and operating costs.

1.2 Summary

The first step in evaluating water recycle/reuse options for power plants was to select five typical plant situations. The four main criteria used in selecting the five plants for study are location, availability, site characteristics, and project timing. Table 1-1 presents the five plants selected for study and a general description of the water systems found at each plant. A detailed discussion of the plants condsidered and the criteria used for selection is presented in Appendix A. A summary of the plant water system alternatives, including rough economics for comparison purposes, for the five plants studied is presented in Section 5.0 (beginning on p. 70).

TABLE 1-1. SELECTED PLANTS FOR WATER RECYCLE/REUSE STUDY

Utility	Plant	Location	Capacity, Mw	Type Cooling[1]	Ash Handling[2]	Part. Control[3]	SO_2 Control[4]
Arizona Public Service	Four Corners	Farmington, New Mexico	2,150	CP	WSB WSF	ESP, Venturi	UC
Public Service of Colorado	Comanche	Pueblo, Colorado	700	WCT	WSB	ESP	None
Georgia Power Co.	Bowen	Taylorsville, Georgia	3,200	WCT	WSB WSF	ESP	None
Pennsylvania Power and Light	Montour	Washingtonville, Pennsylvania	1,500	WCT	WSF WSB	ESP	None
Montana Power Co.	Colstrip	Colstrip, Montana	700	WCT	WSB WSF	Venturi	Lime/alkaline fly ash scrubbing

---

[1] WCT = wet cooling tower, CP = cooling pond

[2] WSB = wet sluicing of bottom ash, WSF = wet sluicing of fly ash

[3] ESP = electrostatic precipitator

[4] UC = under construction

Once the five plants were chosen, spot samples of the major water streams in each plant were taken to aid in characterizing each plant's water system. These samples were taken for only one day's operation and represent operating conditions on that day only. Additional sample analyses to more fully characterize a plant's water system would be required before any of the water recycle/reuse alternatives in this study would be implemented. The results from the samples taken are presented in Appendix B. Makeup waters to the plants varied from about 60 mg/ℓ total dissolved solids to about 450 mg/ℓ total dissolved solids.

In order to evaluate $CaCO_3$ and $Mg(OH)_2$ scale potential in new process configurations for power plant water systems, experimental work was conducted to determine precipitation rates as a function of relative saturation for these species. The results of these experiments (see Appendix C) show that at a relative saturation of about 2.5 for $CaCO_3$ and about 3.4 for $Mg(OH)_2$, there is a sharp increase in precipitation rates due to nucleation. This indicates that at relative saturations above 2.5 for $CaCO_3$ and 3.4 for $Mg(OH)_2$, scale formation is likely.

In addition to the experimental studies concerning $CaCO_3$ and $Mg(OH)_2$, laboratory studies were conducted to determine the solubility characteristics of fly ash collected from each of the five plants. These data were collected to enable evaluation of recirculating ash sluice systems. The results of these studies for the Montour and Colstrip ashes are presented in detail in Appendix D. The results for the remaining three plants are presented in detail in the final report for EPA Contract No. 68-02-1319, Ash Characterization Studies, which was performed in support of this program. This report is included as Appendix L.

Computer process models were used to investigate various recycle/reuse alternatives at the five selected power plants. The models used in this study are discussed in detail in Appendix E. Detailed discussions of the studies conducted at each plant are presented in Appendices F-J. It should be noted here that these analyses were performed to study general water recycle/reuse alternatives. Actual implementation of any of the alternatives would require a more extensive investigation of process parameter variability. Additional data concerning makeup water quality, fuel composition and seasonal flow and load variations would be required before a detailed design could be made. The types of major water systems encountered at these plants include cooling towers, bottom and fly ash sluicing, and particulate/SO_2 scrubbing.

In Sections 2.0-4.0, the results of the plant studies are summarized into discussions of water recycle/reuse options in cooling towers, fly ash sluicing, and particulate/SO_2 scrubbing systems. Section 5.0 discusses combined system alternatives for each of the five plants studied and presents the rough economic estimates for comparison of alternatives at each plant. It should be emphasized here that the rough cost estimates were made for comparative purposes only and may not be representative of the actual cost to be expected for implementing particular alternatives. Retrofit problems were not considered in the cost estimates since evaluation of retrofit would necessitate forming a detailed design of each alternative.

1.3 Conclusions and Recommendations

The major tool used in this study was a computer simulation package capable of modeling the major water consumers (cooling tower, ash sluicing, and scrubbing systems) at coal-fired electric power plants. The models used were verified using the results of spot samples taken at five different plants. The verified models were used to evaluate various water recycle/reuse opportunities at each of these five power plants. The results of the computer simulations showed that improvements over existing operations could be made which would reduce water use and discharge.

In cooling tower cases where $CaCO_3$ or $CaSO_4 \cdot 2H_2O$ are the limiting scale-forming species, recirculation of the cooling water may be increased so that the entire blowdown can be used as makeup to another major water consumer(s) in the plant. Sulfuric acid addition and/or lime softening may be required to achieve this degree of recirculation depending on the plant makeup water quality. Kinetic studies such as those presented in Appendix C for $CaCO_3$ and $Mg(OH)_2$ are recommended for silica-based scale-forming species so that the maximum safe degree of recirculation in tower systems where these solids are limiting may be more adequately defined. Other factors which may limit the cycles of concentration in cooling towers are the chloride level and the suspended solids level. High chloride concentrations may cause corrosion problems. High suspended solids concentrations (from makeup water or scrubbed from the air) can cause erosion and plugging in the condenser.

Most fly ash sluicing operations are once-through with the ash pond overflow discharged. This study revealed that recirculating fly ash sluice systems may be used but treatment may be necessary to control gypsum scale potential. The amount of leachable species in the ash and the makeup water quality are the major parameters which determine the level of treatment required. The computer simulations performed for recirculating ash sluicing systems were based on ash reactivity determined from beaker leaching studies, and represent "worst case" operation.

Bench-scale experiments showed that ash reactivity varies considerably with liquor pH and composition. Pilot or additional bench-scale studies are recommended to more accurately determine the reactivity of a particular ash before implementing a recirculating fly ash sluice system.

Carbon dioxide transfer to the pond liquor from the atmosphere increases $CaCO_3$ and decreases $Mg(OH)_2$ scale potential in recirculating ash sluice systems. Installation of reaction vessels prior to the slurry line may allow controlled precipitation of these solids to prevent line plugging. Pilot or bench-scale studies are recommended to better identify $CaCO_3$ and/or $Mg(OH)_2$ scale potential for a particular ash before a recirculating system is built.

Since lime-based SO_2/particulate scrubbing systems may be operated in a closed-loop fashion, there is little opportunity for recycle/reuse within the scrubbing system. However, cascaded water may be used as scrubber makeup water (excluding demister wash) in the final step of the cascaded system, resulting in zero discharge. Possible sources for the cascaded water are cooling tower blowdown and ash pond overflow. Combining cascaded water with fresh makeup water and using this mixture as demister wash may be feasible depending on the respective water compositions and the amount of SO_2 removed in the demister. A careful process analysis and pilot studies are suggested for determining the quality of water required for demister wash in a particular scrubbing system.

The results of this study point out that computer models are effective in identifying water recycle/reuse options in cooling tower, ash sluicing, and SO_2/particulate scrubbing systems. However, the use of these predictions for designing actual modifications is limited by the model assumptions and the input data. The major assumption made in the cooling tower models is that complete CO_2 equilibrium between the circulating water and the atmosphere is achieved in the tower. If equilibrium is only approached, higher total carbonate concentrations than predicted will be observed in the system. This will cause the observed pH to be lower than predicted. This lower pH will make the scaling potential of $CaCO_3$ lower since the pH has a greater effect on $CaCO_3$ scale potential than the total carbonate concentration. The cooling tower models' results should therefore represent a slightly conservative mode of operation with respect to scaling, but this should have a small effect on acid requirements, so the acid rates predicted should be realistic.

The ash sluicing model predictions are perhaps overly conservative since the ash reactivity was assumed to be constant and equal to the amount leached by deionized water. This represents a "worst case" operation since bench-scale ash sluicing experiments showed that more concentrated liquors tended to leach less from the ash. The actual degree of CO_2 transfer occurring in ash ponds also has not been adequately defined. Computer simulations were performed to bound the level of CO_2 transfer by assuming equilibrium with the atmosphere in one case and no transfer in another. The actual amount of transfer will be between these two predictions.

The scrubbing models used in this study are based on precipitation kinetics data and material and energy balances. A key assumption in the scrubbing model is the amount of SO_2 sorbed that is oxidized. Required reaction tank volumes will vary considerably with oxidation since in most cases they are sized based on $CaSO_4 \cdot 2H_2O$ relative saturation. The cases studied all assumed greater than 90% oxidation and therefore represent a worst case situation. If less oxidation occurs, the predicted hold tank volume and $CaSO_4 \cdot 2H_2O$ relative saturation will be overly conservative with respect to gypsum scale formation.

The input data to all of these models were based on design operating parameters where available. Oxidation in the scrubbing systems was assumed to remain at the level determined from the spot samples. Makeup water compositions were also based on spot samples. These spot samples represent one day's operation and do not reflect variations in the water quality. Although spot samples are sufficient for preliminary judgements, additional data concerning process parameter variability would be required to safely predict conditions under alternative operating conditions.

2.0 COOLING SYSTEMS

Approximately 40 percent of the energy produced in the boiler of a coal-fired steam-electric generating plant leaves the plant in the form of electricity. The remaining 60 percent leaves the plant as waste heat with the stack gases and the cooling water. The energy lost with the stack gases is about 10% of the energy rejected by the condensers. Therefore, the largest single end use for the energy consumed at a power plant is in low temperature rejection of warm water from the condensers.

The ultimate disposal of this waste heat can be handled in two basic ways. The least expensive way to supply cooling water to a power plant is via a once-through cooling system. In such a system cooling water is taken from a stream, river, lake or ocean and is rejected, at a higher temperature, at some other point away from the intake. This type of cooling is considered less environmentally acceptable than other methods because of the biological effects associated with warming natural bodies of water. Recently power plants have been built with recirculating cooling systems which reuse the cooling water and dispose of the waste heat to the atmosphere.

Recirculating systems include a broad range of cooling towers and cooling ponds. Wet cooling towers are in more general use because they require less land than do cooling ponds, and are much less expensive than dry cooling towers. Wet systems generally reject heat from the cooling water to the atmosphere by sensible heat exchange (~20%) and evaporation (~80%). Dry systems depend entirely on sensible heat transfer to reject their heat. All recirculating cooling systems are more expensive to build and operate than are once-through systems.

Four of the coal-fired steam-electric generating plants studied employ wet cooling towers to dispose of their waste heat. The four plants were Georgia Power Company's Plant Bowen, Colorado Public Service's Comanche SES, Montana Power Company's Colstrip SES, and Pennsylvania Power and Light's Montour SES. These cooling systems were studied and alternative operating modes were suggested which would decrease the water consumption required under normal operating conditions.

In this section the results of these studies will be presented, including a general description of wet cooling towers, as well as the four specific systems studied. This is followed by a description of the important factors which affect cooling tower operation and limit the recycle options. Finally, the proposed alternative operating modes which resulted from this study are presented.

2.1 Process Description

Wet cooling towers serve the function of contacting a recirculating water stream with the atmosphere. To obtain the maximum amount of cooling, these towers bring air and water into intimate contact on the wetted surface of the fill in the tower. Theoretically, the water can reach the ambient wet bulb temperature in the tower, although in actual practice the approach to the wet bulb is closer to 3-8°C. The design of large cooling towers, such as those used in power plants, is therefore highly dependent on the ambient conditions which will be expected during the operational lifetime of the tower.

Wet cooling towers are net water consumers. Losses occur from the tower in three major ways: evaporation, drift, and blowdown. The sum of these three streams is equal to the makeup requirements for the tower. Evaporation accounts for the majority of the water lost from the tower. Drift occurs because fine droplets of water are carried off as a mist due to the intimate contact of the air and water. Most cooling towers have mist eliminators designed to minimize drift. The blowdown is a purge stream which is used to control the level of dissolved solids which will build up in the recirculating water. Figure 2-1 shows the general flow scheme for a cooling tower system including the tower and condenser.

The evaporation and drift rates are set by the design of the tower, the ambient conditions, and the cooling load. The blowdown rate is maintained at a level sufficient to prevent scale formation in the condenser but in many cooling towers the size of the blowdown is much larger than required to prevent scale formation. By better defining the limits of scale formation in recirculating cooling systems, the blowdown can be reduced and thus the net water consumption and discharge from these systems can be reduced. The major effort expended in the cooling tower systems was directed toward reduction of the blowdown required for safe operation.

The four cooling systems studied varied in location, size, and design. Table 2-1 presents information about the design conditions of the different cooling systems. The data are presented for one cooling tower under design summer conditions.

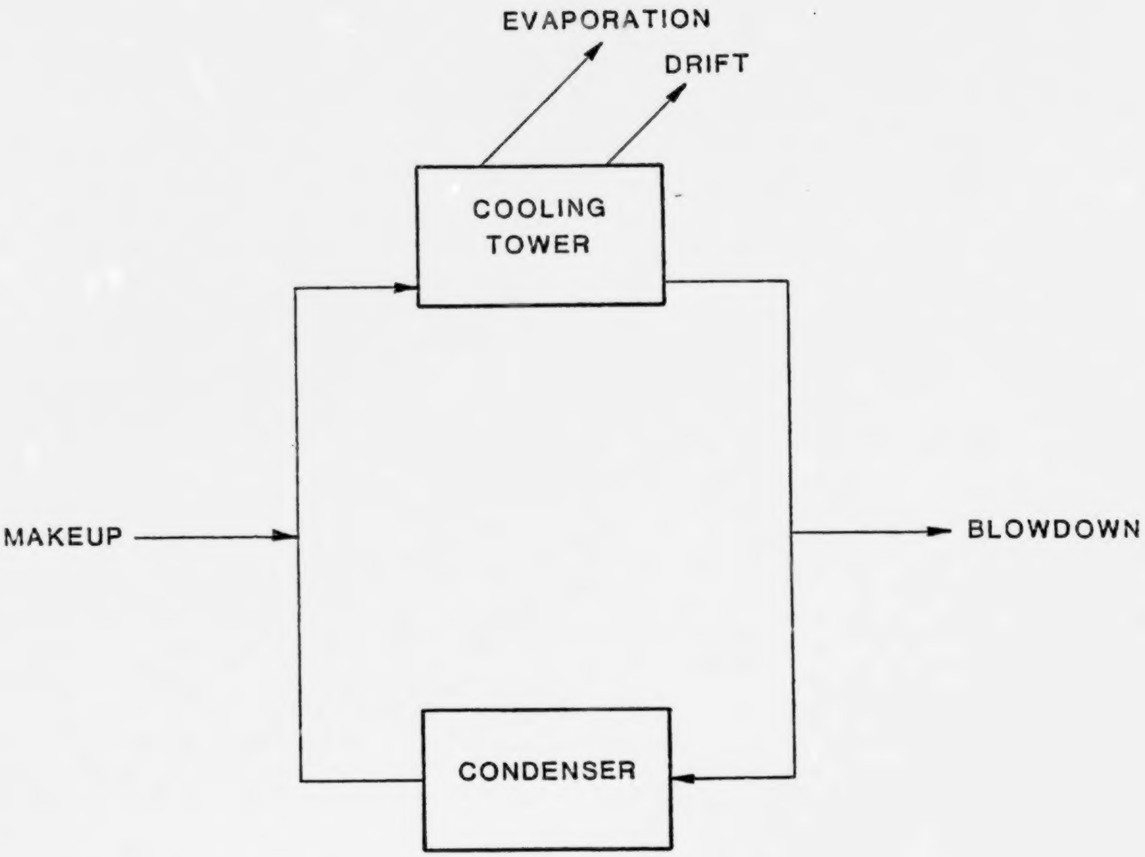

EVAPORATION
DRIFT
COOLING TOWER
MAKEUP
BLOWDOWN
CONDENSER

Figure 2-1. General cooling tower system flow scheme.

TABLE 2-1. COOLING TOWER SYSTEM DESIGN PARAMETERS

	Georgia Power Co.* Plant Bowen	Colorado Public Service Comanche	Montana Power Co. Colstrip	Penn Power & Light Montour
Type	Hyperbolic natural draft	Induced draft	Induced draft	Hyperbolic natural draft
Number of Towers	4	2	2	2
Electric Generating Capacity per Tower, MW	700 880	350	350	750
Circulating Water Rate per Tower, ℓ/sec (GPM)	16,000 (260,000) 19,000 (310,000)	9,100 (145,000)	6,500 (100,000)	15,800 (250,000)
Temperature Change Across Condenser, °C (°F)	14 (26) 16 (28)	14 (26)	18 (32)	16 (28)
Air Flow Rate per Tower, M^3/hr (ACFM)	2.5×10^7 (1.45×10^7) 3.5×10^7 (2.07×10^7)	2.7×10^7 (1.6×10^7)	1.7×10^7 (1.0×10^7)	3.5×10^7 (2.06×10^7)
Cooling Tower Drift Rate, ℓ/sec (GPM)	3.3 (52) 3.4 (62)	9.0 (142)	1.3 (20)	31.5 (500)
Cooling Water Approach, °C (°F)	11 (19) 10 (18)	8 (15)	12 (22)	10 (19)
Evaporation Rate per Tower, ℓ/sec (GPM)	340 (5,500) 400 (6,500)	190 (3,000)	160 (2,600)	390 (6,200)

*Plant Bowen has cooling towers of two different sizes. The first line refers to Units 1 & 2 and the second line refers to Units 3 & 4.

Two different sizes of towers are used at Plant Bowen and the data for both sets of towers are presented.

Comanche and Colstrip have induced draft cooling towers. This is the most common type of cooling tower found in the United States. Induced draft towers have large fans mounted in the top of the towers which move the air which contacts the cooling water. The cooling towers at Bowen and Montour are hyperbolic natural draft towers. The natural draft towers do not use fans to move the air through the tower, but instead take advantage of the buoyancy effects that occur when the air is heated to a temperature higher than the ambient dry bulb temperature. Natural draft towers therefore require high relative humidities to operate effectively, such as the conditions found in the eastern part of the United States.

The design parameters for the temperature change across the condenser, and the cooling water approach do not vary much among the different tower designs. The remaining parameters do not compare readily because of the large differences in the power generating capacities of the different plants that the towers serve. Table 2-2 presents parameters for the different plants on a normalized basis. The parameters presented in this table show that they do not vary widely from plant to plant.

The cooling towers at Colorado Public Service's Comanche SES are the most conservatively designed. The towers at Comanche are designed to discharge 360 kcal/sec per MW of electric generating capacity, the largest value for the four plants. Also, Comanche has the largest air and water flow rates per MW, with the design air flow rate more than twice as large as the normalized air flow for towers 1 and 2 at Bowen. The design drift rates reported are values that the cooling tower manufacturer guarantees the drift will not exceed. Drift rates are very hard to measure and estimates vary significantly. The values reported in Table 2-2 range from 0.02% to 0.20% of the recirculating water. The evaporation rates from the different towers are in close agreement ranging from 2.1% to 2.6% of the total recirculating water flow.

These cooling systems have been chosen as a sample of the cooling towers presently in use by the electric utility industry in the United States. In the next section the important variables that affect the reuse options available to these cooling systems will be identified.

TABLE 2-2. NORMALIZED COOLING TOWER DESIGN PARAMETERS

	Georgia Power Co.* Plant Bowen	Colorado Public Service Comanche	Montana Power Co. Colstrip	Penn. Power & Light Montour
Circulating Water Rate, ℓ/sec per MW (GPM/MW)	23 (365) 21 (333)	26 (412)	19 (300)	21 (333)
Air Flow Rate, m^3/hr per MW (ACFM/MW)	3.6×10^4 (2.1×10^4) 3.9×10^4 (2.3×10^4)	7.7×10^4 (4.5×10^4)	4.9×10^4 (2.9×10^4)	4.7×10^4 (2.8×10^4)
Cooling Load, kcal/sec per MW (Btu/min·MW)	320 (7.6×10^4) 340 (8.1×10^4)	360 (8.6×10^4)	330 (7.9×10^4)	340 (8.1×10^4)
Drift Rate, % of recirculating water	0.02 0.02	0.10	0.02	0.20
Evaporation Rate, % of recirculating water	2.1 2.1	2.1	2.6	2.5

*Plant Bowen has towers of two different designs. The first line refers to Units 1 & 2 and the second line refers to Units 3 & 4.

2.2 Process Variables

The major problem associated with the increased recycle of cooling water in wet cooling tower systems is the danger of scale formation in the condenser. Scale can form on the tubes of the condenser, reduce the efficiency of the condenser, increase the back pressure in the turbine, and therefore reduce the efficiency of the plant. The potential for scale formation is a function of the temperature of the cooling water as well as the water quality. The composition of the recirculating water is a function of the makeup water quality and the cycles of concentration. In this section the general effects of cycles of concentration on water quality and scale potential will be discussed. These effects will be quantified in Section 2.3.

2.2.1 Cycles of Concentration

The cycles of concentration is defined as the ratio of the recirculating species concentration to the makeup species concentration and can be expressed in terms of flow rates by Equation 2.1:

$$C = \frac{E + B + D}{B + D} = \frac{M}{B + D} \qquad (2.1)$$

where

C = cycles of concentration

E = evaporation rate

B = blowdown rate

D = drift rate

M = makeup rate

This expression is a direct result of a mass balance of the conserved dissolved species around the cooling tower.

Water enters the system as makeup and leaves by evaporation, blowdown, and drift. The dissolved species enter the system in the makeup and leave in the blowdown and drift. The concentrating effect of the wet cooling tower occurs because of the large amount of water which leaves the system via evaporation.

The concept of cycles of concentration can be used to calculate the concentrations of individual dissolved solids in the recirculating water from the makeup water concentrations. As the cycles of concentration increase, the recirculating water species concentrations increase as does the potential for scale formation in the condenser. The blowdown stream is used to control the cycles of concentration. As the blowdown decreases, the cycles of concentration increases as can be seen from Equation 2.1. The major thrust of this study was to minimize the blowdown requirements from the cooling tower without increasing the cycles of concentration beyond the point of safe operation.

2.2.2 Relative Saturation

In this study the potential for scale formation was quantified using the concept of relative saturation. Relative saturation is a measure of the degree of the saturation of a solution with respect to precipitation of a particular solid and is related to the thermodynamic stability of that solid. As an example, the relative saturation of $CaCO_3(s)$ can be expressed with the following equation:

$$R.S._{CaCO_3} = \frac{a_{Ca^{++}} \cdot a_{CO_3^=}}{K_{CaCO_3}} \qquad (2.2)$$

where

$R.S._{CaCO_3}$ = relative saturation of $CaCO_3$

$a_{Ca^{++}}$ = activity of free calcium ion in solution

$a_{CO_3^=}$ = activity of free carbonate ion in solution

K_{CaCO_3} = solubility product constant for calcium carbonate

The relationship between the total calcium and carbonate present and the free ion activity is explained in Appendix E. Some of the calcium and carbonate will be complexed with other ions. Thus, the free ions represent only part of the total species present.

When the relative saturation for any species is less than one, the species is subsaturated and no solid formation occurs. When the relative saturation is greater than one, the species is supersaturated and scale may form. In the presence of seed crystals, the relative saturation of a species may exceed 1.0 without scale formation, but solids precipitation will occur in a controlled fashion by seed crystal growth. However, as relative saturation increases above 1.0, a critical value is reached where precipitation occurs through crystal growth and nucleation. When nucleation occurs, the precipitation rate increases rapidly resulting in conditions favorable to scale formation.

In this study $CaSO_4 \cdot 2H_2O$, $CaCO_3$, $Mg(OH)_2$, and silicate scale potentials were calculated. Kinetic studies have been performed which determined that the critical relative saturation of $CaSO_4 \cdot 2H_2O$ is 1.3-1.4. Kinetic studies reported in Appendix C determined that the critical relative saturations for $CaCO_3$ and $Mg(OH)_2$ are about 2.5 and 3.4, respectively. The kinetics of silicate scale was not studied in this program and literature results are insufficient to determine critical relative saturations.

From the form of Equation 2.2 it can be seen that the relative saturation of the different scale-forming species should increase as the concentration of the dissolved solids increase. In this study, operating conditions for cooling towers were designed to maintain the relative saturation of all species less than or equal to one for the options presented. This allowed for a margin of safety equal to the difference between the critical relative saturation and one.

2.3 Treatment Options

The blowdown from a cooling tower system is used to control the level of the dissolved solids in the recirculating water. Blowdown alone can be used to control the scaling potential of the recirculating water as is presently done at Bowen and Montour. Other methods also exist which will reduce the scale potential of particular solids. These methods include acid treatment for pH control, lime softening to reduce the level of calcium, and the use of a wide range of scale inhibitors. In this study, the use of inhibitors was not considered due to the proprietary nature of many inhibitors and the complex chemistry involved. A discussion of the treatment options which can be used to decrease the discharge from cooling systems is presented along with the impact of new operating modes in this section.

2.3.1 Acid Treatment

Sulfuric acid is often used in cooling towers to control the pH of the recirculating water. $CaCO_3$, $Mg(OH)_2$, and some of the silicate scales are more soluble in lower pH solutions. In this study, sulfuric acid was used to keep these scales from forming at increased cycles of concentration. The relative saturation of $Mg(OH)_2$ was well below one for all cases where acid addition was used to control $CaCO_3$ scale potential so the acid addition rate was calculated based on $CaCO_3$ relative saturation in these studies.

The relative saturation of $CaCO_3$ is directly dependent on the activities of Ca^{++} and $CO_3^=$ as can be seen in Equation 2.2.

$$R.S._{CaCO_3} = \frac{a_{Ca^{++}} \cdot a_{CO_3^=}}{K_{CaCO_3}} \qquad (2.2)$$

The concentration and therefore the activity of the carbonate ion is dependent on the total carbonate species in solution (H_2CO_3, HCO_3^-, $CaHCO_3^+$, $CaCO_3$, $MgHCO_3^+$, $MgCO_3$, $NaHCO_3$, $NaCO_3^-$, and $CO_3^=$) and the equilibrium distribution of these ions. A major equilibrium relationship is the one between the carbonate and bicarbonate ions shown in Equation 2.3.

$$HCO^-_{3(aq)} \rightleftarrows H^+_{(aq)} + CO^=_{3(aq)} \qquad (2.3)$$

From Equation 2.3 it can be seen that an increase in pH (decreasing the H^+ concentration) has the effect of shifting the reaction to the right and increasing the concentration of the carbonate ion.

Since CO_2 transfer can occur between the air and the water in the cooling tower, the total amount of carbonate species is a function of the equilibrium shown in Equation 2.4.

$$CO_{2(g)} + H_2O_{(1)} \rightleftarrows H_2CO_{3(aq)} \qquad (2.4)$$

As the pH increases, this equilibrium tends to shift to the right, increasing the total amount of carbonate species in solution.

The above equations point out the strong effect pH has on the relative saturation of $CaCO_3$. They also show that the relationship between pH and the relative saturation of $CaCO_3$ is not simple. It is important to account for these factors when determining the amount of acid that must be added to control the relative saturation of $CaCO_3$.

In this study a computer model of the cooling tower systems (Appendix E) was used to determine the amount of acid treatment required to keep the relative saturation of $CaCO_3$ below one. This model takes into account the equilibrium relationships among the dissolved species as well as the gas/liquid equilibrium described in Equation 2.4. Given the inputs of air flow, temperature and composition, makeup water composition, flow and temperatures of the circulating water, drift rate, and cycles of concentration, the model performs iterative calculations around the cooling loop to determine the blowdown, evaporation and makeup rates, and compositions for all water streams. An acid addition rate is determined to keep the $CaCO_3$ relative saturation within a specified range (less than 1.0). If slipstream softening is required (determined by model) the slipstream and chemical addition rates are calculated. Several assumptions are inherent in performing cooling tower simulations and are listed below:

1) Equilibrium exists between CO_2 and H_2O in the atmosphere and the cooling tower exit water.

2) The temperature of the cooled water stream approaches the wet bulb temperature of ambient air within a predictable range.

3) The compositions and temperatures of the cooled water and drift streams are equal.

4) Softening calculations are based on a calcium reduction to 50 mg/ℓ to account for treatment inefficiencies.

The assumption involving the temperature of the cooled water stream is a recognized design parameter in cooling tower evaluation and gives a good approximation. The assumption concerning the temperature and composition of the drift stream should be very close to actuality as is the assumption in regard to H_2O gas-liquid equilibrium. The assumption with regard to CO_2 equilibrium is conservative since the partial pressure of CO_2 in actual cooling towers tends to be greater than the equilibrium value. The lower equilibrium concentration of carbonate species, assumed in the model, causes the pH to be slightly higher in the model than in actual operation. The higher pH causes the relative saturation of $CaCO_3$ to increase more than the lowered carbonate species concentration causes it to decrease.

Figure 2-2 presents the calculated acid addition rate required to control $CaCO_3$ scale as a function of cycles of concentration for the cooling systems at Montour and Bowen, two systems that presently operate without acid addition. This graph shows that the acid required to control $CaCO_3$ rises with the cycles of concentration in a non-linear fashion. It also shows that the change in acid requirements as a function of cycles (the slope) varies with makeup water composition. Both plants presently operate their cooling towers at less than 3 cycles of concentration and relative saturations of $CaCO_3$ much less than one. Performing simulations of these systems has shown that the makeup water requirements as well as the blowdown can be reduced using only sulfuric acid to inhibit $CaCO_3$ scale formation.

The makeup water quality determines which species are most likely to scale. The water used for makeup at Comanche is high in silica. The relative saturation of SiO_2 in actual plant operation with acid addition is 1.36, and that of $CaCO_3$ is less than 10^{-3}. When considering alternatives for the Comanche cooling towers, the relative saturation of SiO_2 is much more important than $CaCO_3$. Since scaling in the condensers does not presently occur at Comanche, the critical relative saturation for $SiO_{2(s)}$ formation is most likely above 1.36. Kinetic studies, such as those presented in Appendix C for $CaCO_3$ and $Mg(OH)_2$, for silica and other silicate solids should be performed to determine the critical relative saturation necessary for homogeneous nucleation. When the critical values for the silica and other silicate scale is determined, estimates of the acid requirements for the Comanche system can be more accurately estimated.

2.3.2 Calcium Removal

There are some scale forming species whose solubility is not affected by the pH of the solution. For these solids acid addition is not an effective inhibitor. In the cooling tower systems studied, the only scale forming species which could not be controlled with acid was $CaSO_4 \cdot 2H_2O$ (gypsum). Equation 2.5 presents the equilibrium relationship affecting $CaSO_4 \cdot 2H_2O$ solid formation.

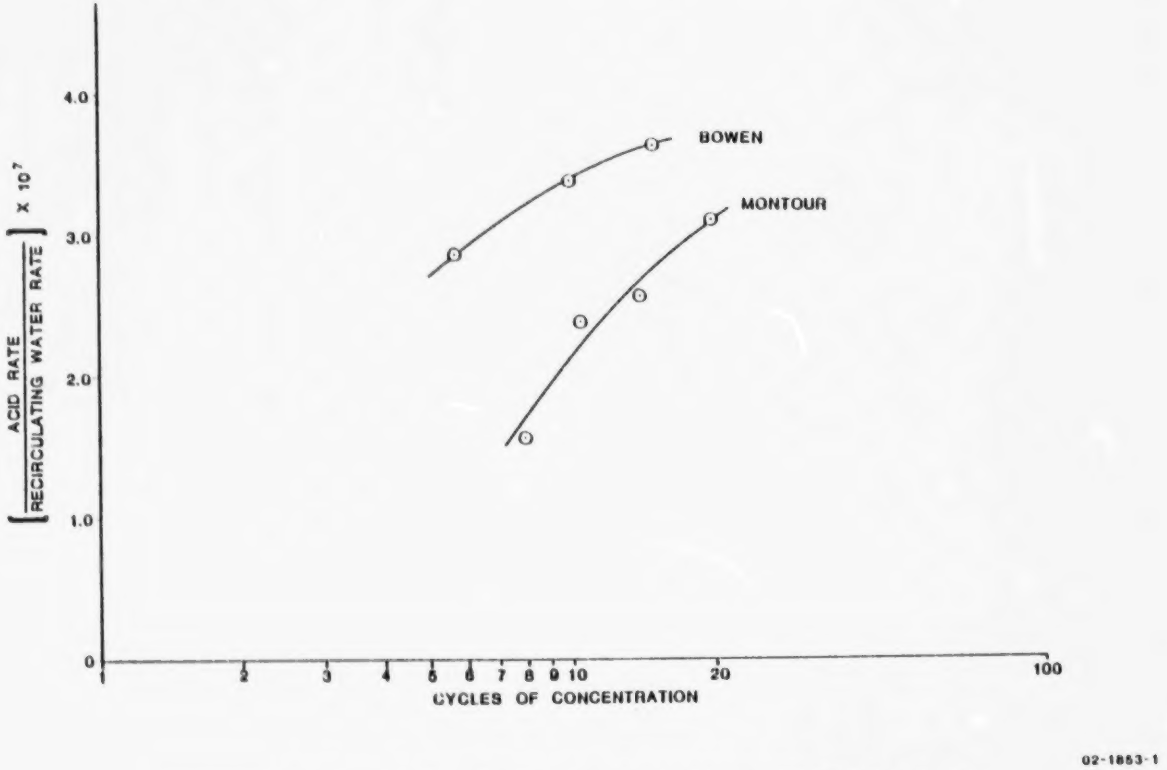


Figure 2-2. Calculated acid requirements as a function of cycles of concentration.

$$CaSO_4 \cdot 2H_2O_{(s)} \rightleftarrows Ca^{++}_{(aq)} + SO_4^{=}{}_{(aq)} + 2H_2O \qquad (2.5)$$

The relative saturation of $CaSO_4 \cdot 2H_2O$ can be calculated using Equation 2.6.

$$R.S._{CaSO_4 \cdot 2H_2O} = \frac{a_{Ca^{++}} \cdot a_{SO_4^{=}} \cdot a^2_{H_2O}}{K_{CaSO_4 \cdot 2H_2O}} \qquad (2.6)$$

$$= \frac{(\gamma_{Ca^{++}} \cdot m_{Ca^{++}}) \cdot (\gamma_{SO_4^{=}} \cdot m_{SO_4^{=}}) \cdot (\gamma_{H_2O} \cdot m_{H_2O})^2}{K_{CaSO_4 \cdot 2H_2O}}$$

where

$R.S._{CaSO_4 \cdot 2H_2O}$ = relative saturation of $CaSO_4 \cdot 2H_2O$ (gypsum)

$K_{CaSO_4 \cdot 2H_2O}$ = solubility constant for calcium sulfate dihydrate

$a_{Ca^{++}}$ = activity of calcium ion in solution

$a_{CO_3^{=}}$ = activity of carbonate ion in solution

a_{H_2O} = activity of water in solution

$m_{Ca^{++}}$ = molality of calcium ion in solution

$m_{CO_3^{=}}$ = molality of carbonate ion in solution

m_{H_2O} = molality of water in solution

$\gamma_{Ca^{++}}$ = activity coefficient of the calcium ion in solution

$\gamma_{SO_4^{=}}$ = activity coefficient of the sulfate ion in solution

γ_{H_2O} = activity coefficient of water

If ideal solution is assumed ($\gamma_{Ca^{++}} = \gamma_{SO_4^=} = \gamma_{H_2O} = 1$)

$$R.S._{CaSO_4} = \frac{m_{Ca^{++}} \cdot m_{SO_4^=}}{(K_{CaSO_4 \cdot 2H_2O}/(m_{H_2O})^2)} \qquad (2.7)$$

The calcium level and the sulfate level should be functions of the cycles of concentration. Figure 2-3 shows how the relative saturation of $CaSO_4 \cdot 2H_2O$ varies with the cycles of concentration at the three plants where softening was not used. The lines for Montour and Comanche are nearly parallel whereas the slope of the line for Bowen is much steeper. At Bowen the sulfate added with acid treatment is significant relative to the sulfate added with the makeup water, whereas it is small at Montour and Comanche. In cases where the sulfate ion concentration due to acid addition is small, Equation 2.7 can further be simplified into Equation 2.8.

$$R.S._{CaSO_4} = C^2 \times R.S.^*_{CaSO_4} \qquad (2.8)$$

where

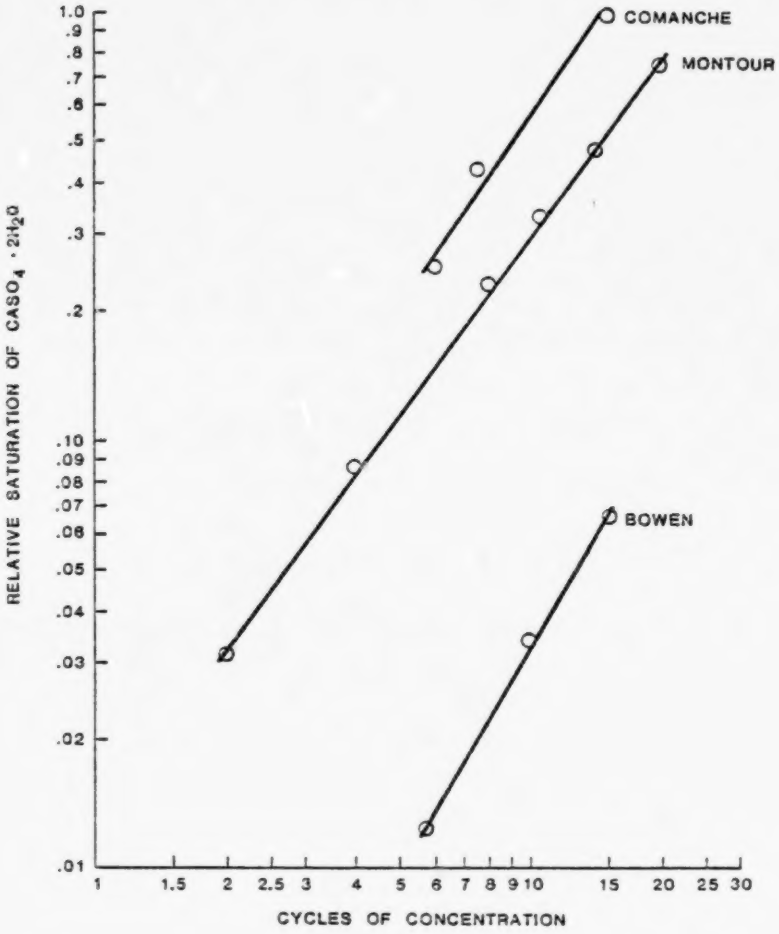
C = cycles of concentration

$R.S.^*_{CaSO_4}$ = the relative saturation of $CaSO_4 \cdot 2H_2O$ in the makeup water (one cycle of concentration)

$R.S._{CaSO_4}$ = the relative saturation of $CaSO_4 \cdot 2H_2O$ in the recirculating water

If the solutions studied were ideal, all of the data plotted in Figure 2-4 would be on the line which represents Equation 2.8. As can be seen from the figure, the actual relative saturation for a given cycles of concentration is substantially less than that predicted by Equation 2.8. This is due to the non-idealities which exist in real systems which cause the activity coefficients of calcium and sulfate to be less than one. Thus, the predictions of scale potential arrived at using ideal solution assumptions can be overly conservative.

Colstrip is the only plant that needs treatment to inhibit gypsum scale in their cooling towers under existing operating conditions. The makeup water to Colstrip has the largest amount of sulfate in solution (about 170 mg/ℓ as $SO_4^=$)



02-1846-1

Figure 2-3. Gypsum relative saturation variation with cycles of concentration.

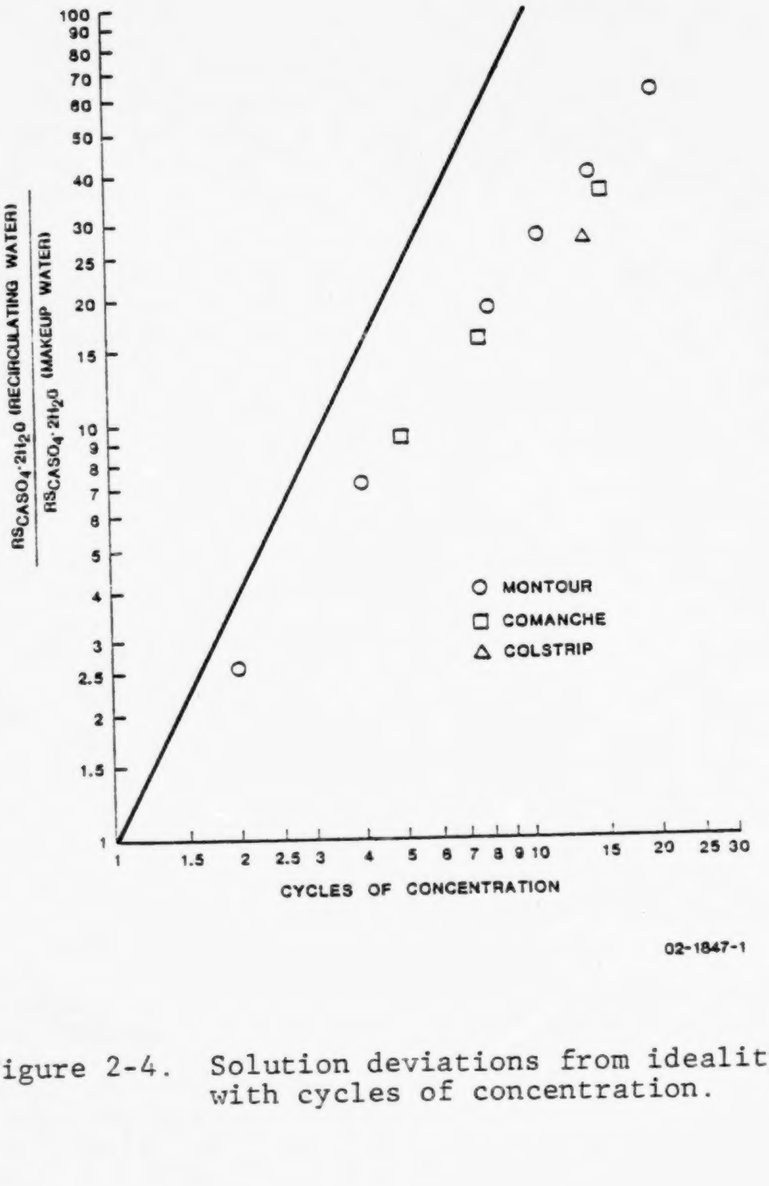


Figure 2-4. Solution deviations from ideality with cycles of concentration.

in addition to operating the towers at the highest cycles of concentration (10-15). Colstrip presently keeps the relative saturation of $CaSO_4 \cdot 2H_2O$ below 1.10 by lime softening of the makeup water.

Softening is a technique used to reduce the calcium concentration in an aqueous stream. In lime softening, $CaO_{(s)}$ is added to the liquid stream to increase the pH of the solution and precipitate $CaCO_{3(s)}$. From Equation 2.6 it can be seen that a reduction in the calcium level reduces the relative saturation of $CaSO_4 \cdot 2H_2O$. Furthermore, softening reduces the relative saturation of $CaCO_3$, and thus the acid requirements to prevent $CaCO_3$ scale. Lime-soda ash softening is similar but non-carbonate hardness and silica removal are also accomplished.

Softening is the least expensive treatment that can be used to control $CaSO_4 \cdot 2H_2O$ scale. Other methods that could be used, such as brine concentration and reverse osmosis, have much higher operating and capital costs. If the gypsum scale potential is not controlled with treatment, the cooling tower blowdown may be excessive. This may require expensive tail-end treatment of the ultimate effluent stream to achieve zero discharge.

Softening is a more expensive treatment method when compared to acid treatment because it requires more expensive equipment and greater maintenance. For this reason, the size of the softened stream can have a major impact on the cost of treatment. A smaller stream to be treated requires lower capital investment for the flocculator and other softening equipment. Higher concentrations of calcium in the stream to be treated require smaller flow rates through the softener to remove the same amount of calcium. The stream with the highest concentration of calcium in most cooling towers is the recirculating water. Often a small slipstream of the recirculating water can be softened and remove as much or more calcium than by pretreating a much larger makeup stream.

Simulations were performed to determine the amount of calcium that must be removed to keep $CaSO_4 \cdot 2H_2O$ subsaturated. In order to account for deviations from equilibrium it was assumed that a softener could effectively reduce the calcium concentration to 50 mg/ℓ. The results of two simulations performed to compare slipstream treatment and pretreatment for the Colstrip cooling system are presented in Table 2-3. In the case of makeup softening, a treatment rate of 175 ℓ/sec was required

TABLE 2-3. EFFECTS OF SLIPSTREAM SOFTENING ON TREATMENT RATE AT COLSTRIP

	Makeup Softening	Slipstream Softening
Cycles of Concentration	13.5	20.0
Makeup Water Rate, ℓ/sec	175.	170.
(GPM)	(2770)	(2700)
Treatment Rate, ℓ/sec	175.	9.0
(GPM)	(2770)	(142)
Calcium Removal Rate, kg $CaCO_3$/day	820.	1040.
(lb/day)	(1800)	(2290)
Blowdown Composition, mg/ℓ		
Calcium	534.	587.
Magnesium	143.	212.
Sodium	540.	1450.
Chloride	227.	964.
Carbonate (as $CO_3^=$)	6.5	25.5
Sulfate (as $SO_4^=$)	2640.	3930.
Nitrate (as NO_3^-)	18.7	33.6
pH	7.2	7.6
$CaSO_4 \cdot 2H_2O$ Relative Saturation*	.93	1.02

*The critical value, above which scale potential exists is 1.3-1.4 for $CaSO_4 \cdot 2H_2O$.

to achieve 13.5 cycles of concentration. With slipstream softening, however, a treatment rate of only 9 ℓ/sec was sufficient to allow operation at 20 cycles of concentration. The calcium removal rate increased from 820 kg $CaCO_3$/day to 1040 kg/day to allow for the increase in cycles of concentration, but the treatment rate decreased due to the large increase in calcium concentration in the stream being softened.

An increase in required calcium removal necessitates a larger slipstream. From Equation 2.6, increases in the concentration of either calcium or sulfate raise the relative saturation of $CaSO_4 \cdot 2H_2O$ and thus increase the calcium removal rate required for scale-free operation. Figures 2-5 and 2-6 show how the required slipstream rate increases as a function of calcium and sulfate concentration in the makeup water when the towers are operated at 20 cycles of concentration (based on sampled Colstrip makeup water).

It should be noted here that these curves apply only to the makeup water composition considered. Variations in other species' concentrations may cause significant changes due to chemical complexing. This curve is valid for the compositions considered and is presented to show trends in the system.

2.4 Recycle/Reuse Alternatives in Cooling Towers

In any cooling system employing cooling towers the cooling water is recirculated. The degree of recirculation is measured by the cycles of concentration. Increasing the cycles of concentration in a cooling tower will reduce the makeup and the blowdown rates but will increase the potential for scale formation. Treatment methods can be employed which will reduce the scale potential of cooling towers which operate at high cycles of concentration.

Two of the plants studied, Bowen and Montour, presently operate their towers at less than three cycles of concentration. Operating in this mode the towers do not need any treatment but do require very large blowdown streams. Simulations of these systems have shown that both plants could increase the cycles of concentration without the risk of $CaCO_3$ scale if sulfuric acid were used to control the pH of the recirculating water. These results show that the blowdown can be reduced by almost an order of magnitude at increased cycles of concentration using only pH control to inhibit scale formation.

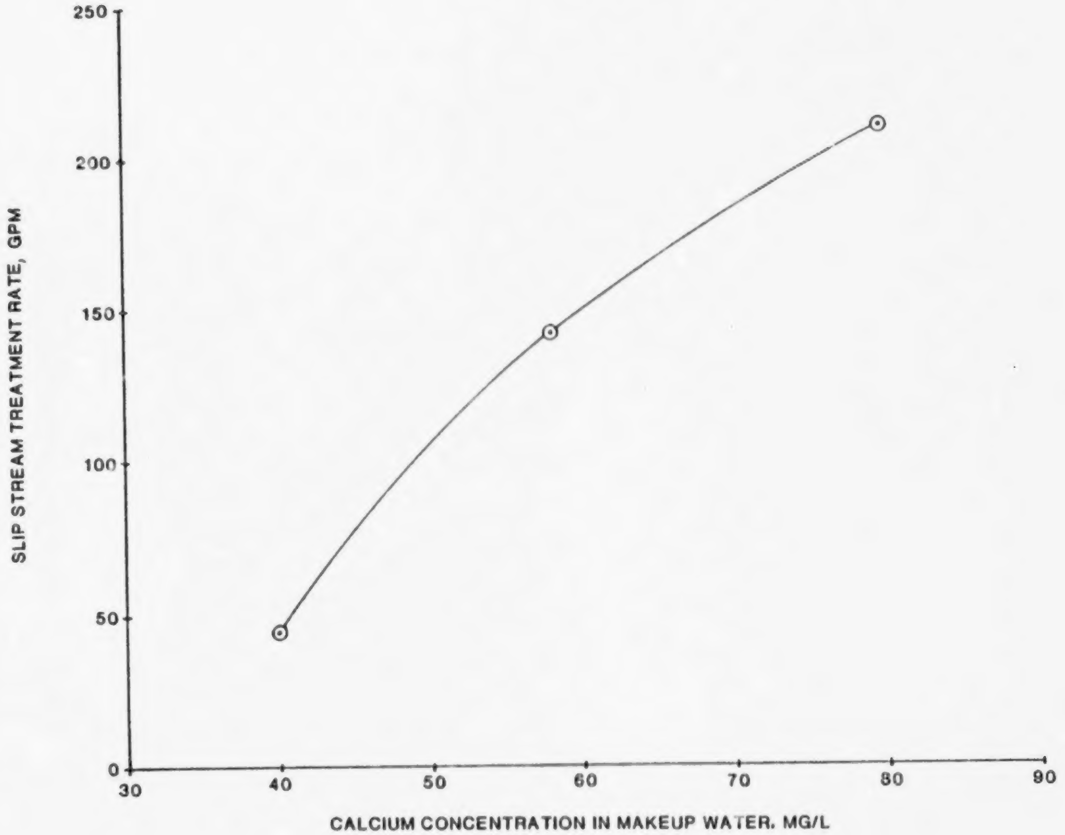


Figure 2-5. Slipstream rate as a function of makeup calcium concentration at Colstrip.

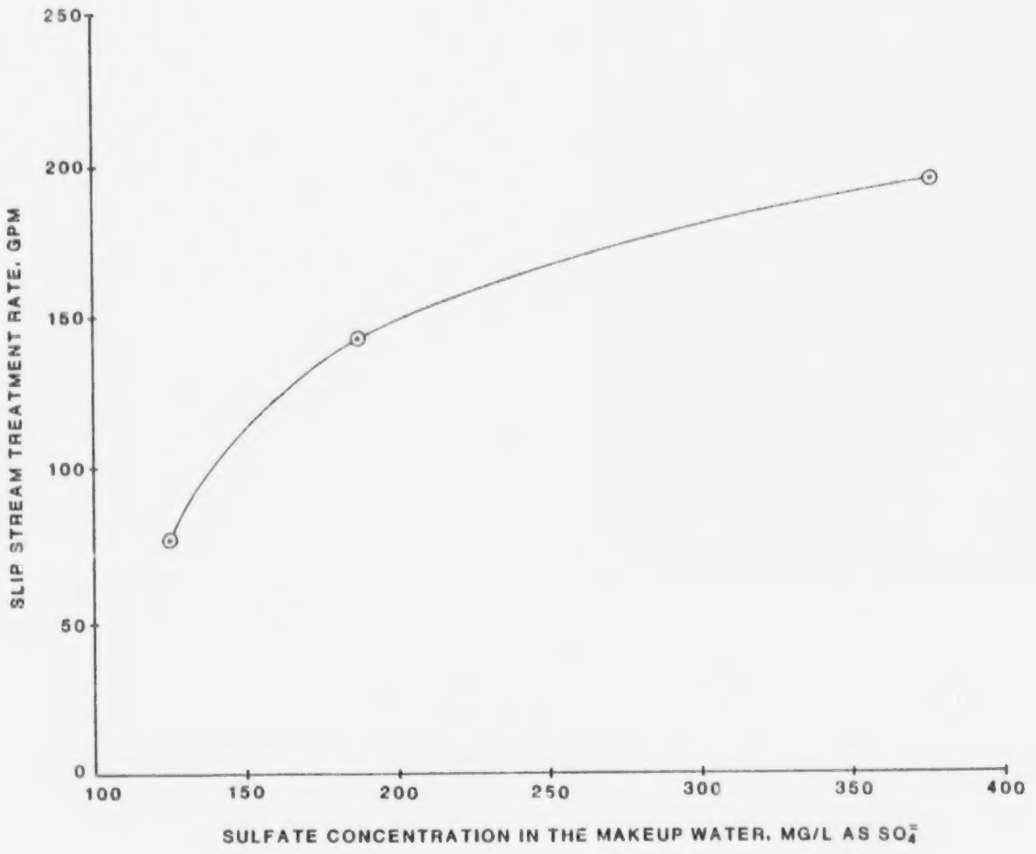


Figure 2-6. Slipstream rate as a function of makeup sulfate concentration at Colstrip.

The cooling towers at Colstrip presently employ pH control and are supplied with softened makeup water. The towers are operated at 10-15 cycles of concentration without scale formation. Simulations of this system have shown that even higher cycles of concentration could be attained if a slipstream from the recirculating water were softened rather than the makeup. This can be accomplished at reduced capital costs because the size of the treated stream is smaller if the slipstream is softened.

The cycles of concentration that can be obtained at Comanche's cooling towers is limited by the potential for silica scale. Comanche's towers presently operate supersaturated with respect to SiO_2 but no significant scale has been noticed in the condensers. Without conclusive kinetic data with respect to SiO_2 formation, simulations of the cooling towers are not sufficient to determine what cycles of concentration Comanche can operate at safely.

In order to minimize makeup water requirements and blowdown rates, cooling towers should be operated at the highest cycles of concentration which will not produce scale or corrosion problems in the condensers. The relative saturation of many scale forming species can be reduced by acid addition for pH control. Softening of either the makeup or a slipstream will reduce the relative saturation of $CaSO_4 \cdot 2H_2O$ which cannot be controlled with acid treatment. Utilization of these treatment methods may allow many existing cooling towers to increase their cycles of concentration safely.

Corrosion problems may be encountered in cooling towers operating at high cycles of concentration if the chloride levels are excessive. High chloride levels in the tower makeup may therefore limit the degree of recycle. Removal of chlorides is very expensive, requiring sophisticated treatment such as reverse osmosis or brine concentration.

3.0 ASH SLUICING SYSTEMS

In addition to cooling towers, a major water consumer encountered at the power plants studied in this program is ash sluicing. Of the five plants considered, two employed wet sluicing for fly ash disposal and all five plants used wet sluicing for bottom ash disposal. Georgia Power Company's Bowen Plant and Pennsylvania Power and Light Company's Montour Plant both use cooling tower blowdown to sluice fly ash on a once-through basis for disposal in ash ponds. The ash pond overflow is discharged in both cases. All of the plants sluice bottom ash on a once-through basis except Four Corners and Colstrip, which have recirculating bottom ash disposal systems.

This section first presents a typical ash sluicing flow scheme with discussions of the particular systems studied. The process description is followed by discussions of the various operating parameters and their effects on the design and operation of ash sluicing systems. The final portion of this section discusses how recycle/reuse options in ash sluicing systems may be incorporated in overall plant water systems to minimize water requirements and discharges.

3.1 Process Description

In coal-fired boilers, two types of ash residue are created by combustion of the coal. Fly ash is that portion of the ash which is carried out of the boiler with the combustion gases and bottom ash is the ash remaining in the boiler which collects at the bottom of the boiler. The relative amounts of fly ash and bottom ash produced depend on the type of furnace in which the coal is fired. Burning pulverized coal in a dry-ash furnace will generally result in about 80% of the ash being entrained with the flue gas as fly ash. Cyclone furnaces, however, retain 70-80% of the coal ash as bottom ash leaving only 20-30% as fly ash (BA-465). The fly ash made up 60-80% of the total ash at the five plants studied, as would be expected from dry ash furnaces.

Bottom ash is typically removed from the boiler by periodic washing and subsequent sluicing of the ash to a pond for disposal. Fly ash must be continuously removed from the flue gases to prevent the discharge of large amounts of particulate matter into the atmosphere through the stack. Available methods for removing the fly ash from the flue gas include electrostatic precipitators, mechanical collectors, fabric filters, and wet scrubbers. Fly ash collected by wet scrubbers is disposed of in a slurry form. Arizona Public Service's Four Corners Plant (Units 1-3) and Montana Power Co.'s Colstrip Plant employ wet scrubbing for fly ash collection. The Four Corners fly ash scrubbing system is open loop whereas the Colstrip SO_2/particulate scrubbing system is closed loop. These systems are discussed in Section 4.0 and Appendices F and J. The remaining three plants (Comanche, Bowen, and Montour) and Units 4 and 5 of the Four Corners Plant collect the fly ash with electrostatic precipitators.

Once the fly ash has been collected, it must be transported to a suitable disposal site. This may be accomplished by slurrying the ash with water and pumping it to a pond or by trucking the ash to the disposal site in a dry form. Fly ash collected by the precipitators at Comanche is trucked away in a dry state. At Bowen and Montour, the collected fly ash is slurried to ash ponds (at about 5% solids at Montour and 7% solids at Bowen). Figure 3-1 represents the type of fly ash and bottom ash sluicing operations at Montour and Bowen. The ash is sluiced to the disposal pond where it settles to 40-50% solids. The excess water is discharged as ash pond overflow. Detailed discussions of the Bowen and Montour water systems are presented in Appendices G and I, respectively.

In areas where water is scarce or regulations prohibit discharging ash pond overflow, a portion or all of the excess pond water may be recirculated to sluice ash. Figure 3-2 represents a recirculating ash sluicing system. In the case where all of the excess pond water is recycled, the makeup requirements are determined by the [illegible] evaporation rate and the sludge solids concentration. Recirculating ash sluice systems with blowdown streams are used at both Colstrip and Four Corners for bottom ash disposal. The blowdown at Colstrip is the overflow from the bottom ash pond to the scrubber ponds. This type of ash handling is not typically used for fly ash disposal since the amount of leachable species (mostly calcium, magnesium, sodium, and sulfate) in fly ash is generally much greater than bottom ash.

A recirculating system is much more susceptible to scaling since dissolved solids in the makeup are concentrated in addition to the species leached from the ash. This study concentrates on the feasibility of using recirculating sluicing systems for fly ash disposal. The effects of operating parameters and fly ash reactivity on the scaling tendency in the system are quantified in the following sections.

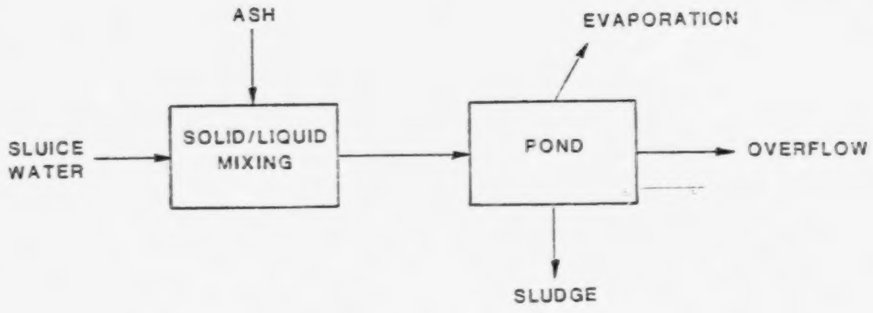

ASH
EVAPORATION
SLUICE WATER
SOLID/LIQUID MIXING
POND
OVERFLOW
SLUDGE

Figure 3-1. Typical once-through ash sluicing flow scheme.

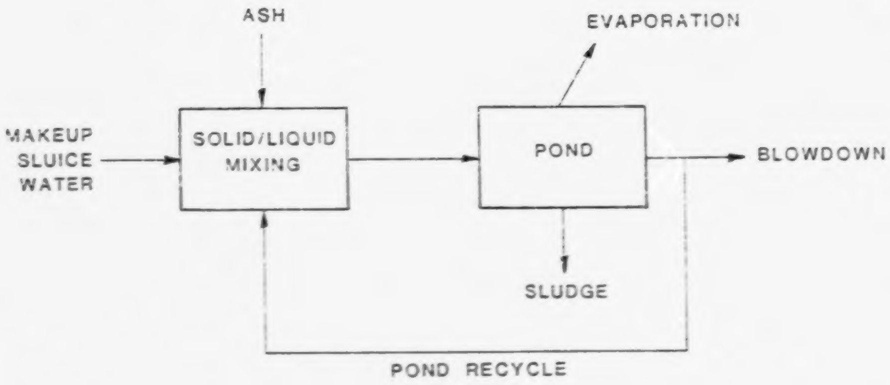

ASH
EVAPORATION
MAKEUP SLUICE WATER
SOLID/LIQUID MIXING
POND
BLOWDOWN
SLUDGE
POND RECYCLE

Figure 3-2. Recirculating ash sluicing flow scheme.

3.2 Process Variables

Two methodologies were used to investigate the effects of operating parameters on the scale potential in recirculating ash sluicing systems. The parameters investigated include ash reactivity, makeup water quality, CO_2 transfer with the atmosphere, and degree of recycle.

First, parametric studies were performed using the ash sluicing computer model. This model calculates the composition of the ash slurry pond, and recycle liquors and determines the scale potential in the system. All flow rates and the amount of soluble species in the ash are the major inputs to the model. First, an overall material balance determines the composition of the pond liquor assuming solid-liquid equilibrium for all species except gypsum. The remaining stream compositions are then calculated based on the amount of leachable species in the ash. No precipitation is allowed in the slurry liquor in order to determine the potential for scale formation by $CaSO_4 \cdot 2H_2O$, $CaCO_3$, and/or $Mg(OH)_2$ solids. Since most of the calculations are either material balances or equilibrium predictions, the validity of the model in predicting scale potential depends on the accuracy of the ash reactivity input to the model. The ash reactivity used as input to the model in this study was obtained from leaching studies using deionized water. Using the ash reactivity determined from the beaker studies is conservative from a standpoint of scale-free operation because fly ash tends to be more reactive in deionized water than in water with a higher level of dissolved solids. In actual operation the water used to slurry the ash has a high enough concentration of dissolved solids to depress the reactivity of the ash.

There are several assumptions which are inherent in performing simulations with the ash sluicing simulation. These include:

1) Solid-liquid equilibrium is achieved in the ash pond, with the exception of $CaSO_4 \cdot 2H_2O$ which is allowed to remain supersaturated.

2) Ash dissolution is essentially complete before the slurry reaches the pond, and supersaturation of all species is allowed in the slurry line.

3) All solids precipitation occurs in reaction vessels or the pond.

The long residence time in an ash pond is sufficient for most of the species to reach solid-liquid equilibrium. Since $CaSO_4 \cdot 2H_2O$ supersaturation has been observed in scrubber ponds, the model did not allow gypsum to precipitate in the pond. The model is also designed to handle varying degrees of CO_2 transfer in the pond. In many cases two simulations were performed, one with no CO_2 transfer and one with CO_2 equilibrium achieved between the pond liquor and the atmosphere. These two cases serve as a boundary on the actual amount of CO_2 transfer occurring. In actual ponds the degree of CO_2 transfer is generally between equilibrium and no transfer. This computer model is discussed in greater detail in Appendix E.

The second methodology used to study ash sluicing involved bench-scale operations. These operations were performed with ash samples collected at the plants and makeup water similar to that measured at these plants. The bench-scale model used a mix tank to combine the sluice water and the ash which was transported to a settling tank which simulated the pond. The pond liquor was then recirculated to the mix tank where it was added to fresh ash and makeup water.

The results of the leaching studies for Montour and Colstrip ash are presented in detail in Appendix K. The bench-scale studies for Montour and Colstrip are discussed in detail in Appendix D. The results of the bench-scale and leaching studies for Bowen, Comanche, and Four Corners ash are presented in the final report for EPA Contract No. 68-02-1319, Ash Characterization Studies, which was performed in support of this program and is included as Appendix L.

3.2.1 Ash Reactivity

Leaching studies were performed to determine the maximum amount of soluble species in the coal ashes from each of the five power plants studied. In these studies, a small amount of ash was mixed with deionized water in a beaker and the pH was periodically adjusted with HCl to maintain a constant value. When no further alkalinity was leached (pH remained constant without acid addition) the liquor was analyzed for calcium, magnesium, sodium, and sulfate. The leachable amount of each species as a fraction of the ash was then calculated.

Table 3-1 presents a summary of the results of the leaching studies performed for the five ashes. These results show that calcium and sulfate are the major species leached from

TABLE 3-1. ASH REACTIVITY DETERMINED FROM LEACHING STUDIES*

Species, wt. %	Montour		Bowen			Four Corners			Comanche		Colstrip		
pH	6.0	8.1	6.0	8.5	10.4	3.0	6.0	8.5	6.0	8.5	4.0	6.0	8.0
Ca	.32	.28	1.3	.76	.56	.83	.71	.62	2.9	2.2	5.1	3.7	3.2
Mg	.02	.02	--	--	--	--	--	--	.11	.05	.66	.21	.06
Na	.04	.04	.12	.10	.07	.02	.02	.02	.04	.03	--	--	--
SO_4	.76	.79	1.3	1.2	1.0	.15	.04	.07	1.2	.83	.55	.60	.57

*Reported as wt. % of ash.

each of the ashes. Magnesium is present in substantial quantity in the Colstrip ash only. The amount of calcium leached decreases with increasing pH for all cases but the sulfate remains relatively constant except for the Bowen and Comanche ashes where it also decreases with increasing pH. The leachable calcium and sulfate as a function of pH for each of the ashes are plotted in Figures 3-3 and 3-4.

The ash reactivity will have a major impact on the feasibility of recirculating ash sluicing systems with respect to gypsum scale formation since significant quantities of both calcium and sulfate may be leached from the ash.

3.2.2 Makeup Water Quality

The composition of the makeup water used in a recirculating ash sluice system will influence the composition of the sluice water and therefore the scaling tendency of the system. Both the bench-scale experiments and the computer model results showed that poorer quality makeup water (greater amounts of calcium and sulfate) increased the gypsum scale potential in the fly ash slurry liquor. Table 3-2 presents results from bench-scale experiments with the Bowen ash and from computer model calculations for the Montour ash. The first two columns represent two closed-loop bench-scale experiments where only the makeup water quality was varied. The first experiment involved poor quality makeup water and a gypsum relative saturation of 1.68, well above the critical value for scale formation, was observed. When a much better quality makeup water was used (lower calcium and sulfate concentrations) the gypsum relative saturation encountered was 1.35, which is significantly lower.

The last two columns in Table 3-2 show the results from two computer simulations of a closed-loop ash sluicing system using the Montour ash. The first simulation involved 8-cycle cooling tower blowdown as makeup water whereas the second simulation used river water as makeup. Again, the gypsum relative saturation decreased (2.8 versus 3.2) when makeup water with less calcium and sulfate was used.

For systems which have gypsum relative saturations greater than 1.3-1.4 (the critical range for scale formation) one treatment option is to use soda ash softening of a portion of the pond recycle liquor. The magnitude of the treatment will depend primarily on the ash reactivity but the makeup water quality will also affect the amount of softening required.

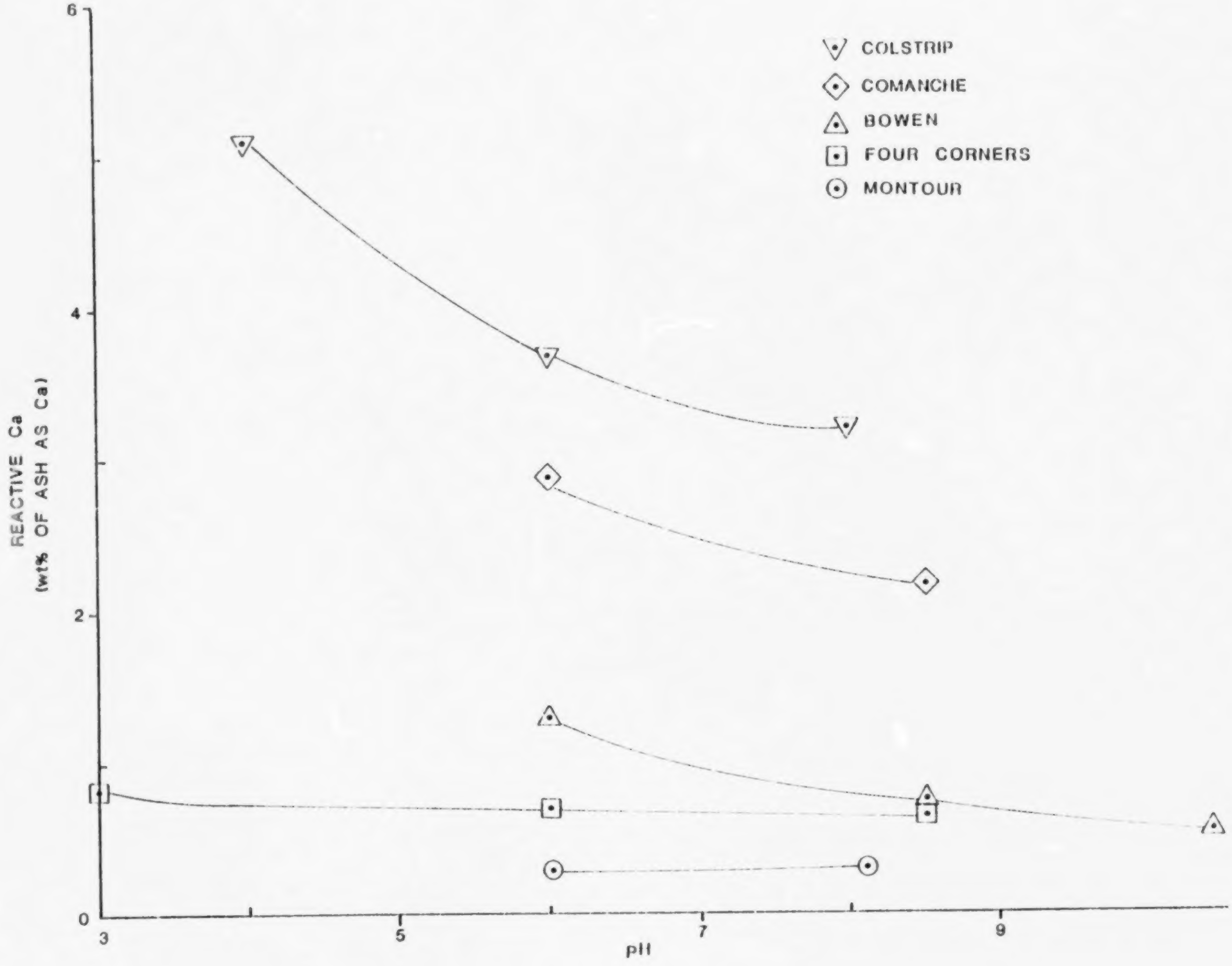


Figure 3-3. Reactive calcium in fly ashes as a function of pH.

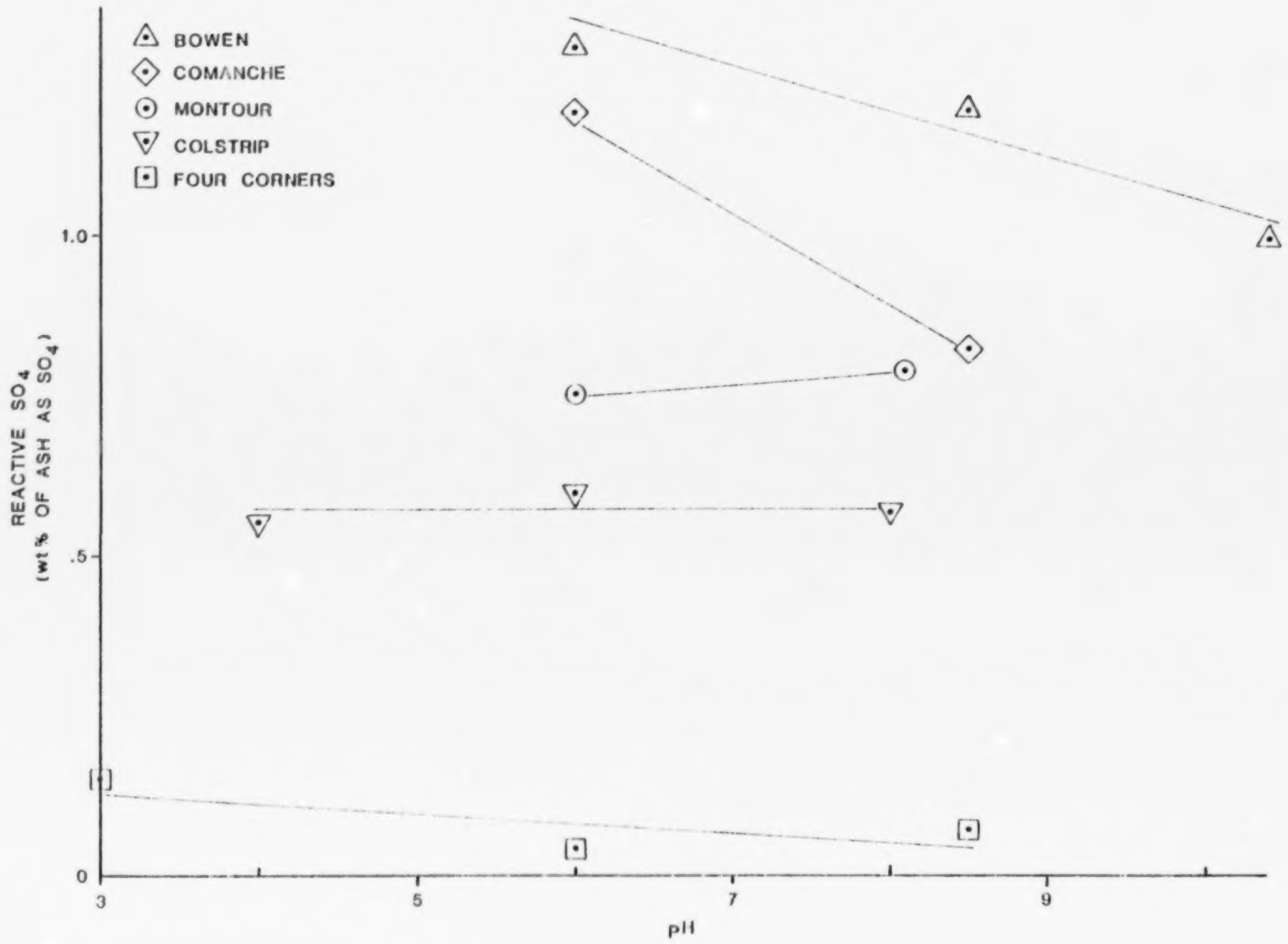


Figure 3-4. Reactive sulfate in fly ashes as a function of pH.

TABLE 3-2. EFFECTS OF MAKEUP WATER QUALITY ON RECIRCULATING ASH SLUICE SYSTEM SCALING POTENTIAL

	Bench Scale Experiments with Bowen Ash		Computer Model Results with Montour Ash*	
MAKEUP WATER, mg/ℓ				
Calcium	205.	30.	227.	28.
Magnesium	66.	8.5	44.	5.5
Sodium	570.	23.	65.	8.
Chloride	50.	8.5	176.	22.
Carbonate (as $CO_3^{=}$)	2.4	100.	30.	6.
Sulfate (as $SO_4^{=}$)	1940.	10.0	555.	6.8
Nitrate (as NO_3^{-})	19.	—	44.	5.5
FLY ASH SLURRY, mg/ℓ				
Calcium	920.	800.	1690.	1500.
Magnesium	2.4	1.2	120.	77.
Sodium	350.	330.	67.	8.4
Chloride	130.	34.	182.	23.
Carbonate (as $CO_3^{=}$)	6.0	6.6	4.	1.4
Sulfate (as $SO_4^{=}$)	2500.	2100.	4350.	3840.
Nitrate (as NO_3^{-})	--	--	46.	5.7
$CaSO_4 \cdot 2H_2O$ Relative Saturation **	1.68	1.35	3.2	2.8
pH	10.6	11.1	10.1	10.2

*No solids precipitation was allowed; calculations were made based on leaching results which represent a worst case situation (i.e., maximum leachable species). Bench-scale experiments gave gypsum relative saturations of 1.1-1.2 for the Montour ash with a reaction tank to allow solids to form.

**Critical value, above which scale potential exists, is 1.3-1.4 for $CaSO_4 \cdot 2H_2O$.

Table 3-3 presents the results of three computer simulations of closed-loop sluicing operations at Montour using slipstream treatment. As the water quality becomes poorer (cycles in cooling tower increase) the amount of pond recycle water which must be treated increases from 27% using river water as makeup to 30% and 36% for 8- and 20-cycle cooling tower blowdown, respectively.

3.2.3 Carbon Dioxide Transfer

In a recirculating ash sluice system, there is potential for CO_2 transfer between the atmosphere and the pond water. The degree of CO_2 transfer will affect the pH of the pond return water and thus the fly ash slurry composition. Since both $CaCO_3$ and $Mg(OH)_2$ relative saturations are pH dependent (tend to precipitate at higher pH), the degree of CO_2 transfer which occurs will have a significant effect on the scaling tendency in the system with respect to these two species.

Table 3-4 presents the results from two of the bench-scale experiments where the only variable between runs was the transfer of CO_2 in the pond. For the run with no CO_2 transfer, no $CaCO_3$ precipitation was noted in the reaction tank even though the relative saturation was 7.8, which is above the critical value of 2.5 (see Appendix C). This may be due to the low carbonate levels in the system (2-5 mg/ℓ). However, when CO_2 was bubbled through the pond liquor, the relative saturation increased to 31.8 and about 2.7 mmole/min of $CaCO_3$ precipitated in the reaction tank. The gypsum relative saturation decreased slightly (from 0.5 to 0.4) due most likely to the precipitation of calcium as calcium carbonate. In every case where the CO_2 bubbler was used in the bench-scale experiments, $CaCO_3$ precipitation was noted in the mix tank (ranging from 0.1 to 2.7 mmole/min), indicating that CO_2 transfer between the pond and the atmosphere could cause $CaCO_3$ scaling problems with recirculating ash sluice systems.

Table 3-5 presents the results from two of the computer model calculations where CO_2 transfer effects were studied. As with the bench-scale experiments, the transfer of CO_2 in the pond increased the $CaCO_3$ scaling potential in the system. A significant increase in the amount of $CaCO_3$ solids precipitated was noted along with an increase in relative saturation. The calculated amount of $CaCO_3$ solids formed increased from 0.03 gmole/sec for the case with no CO_2 transfer to 1.85 gmole/sec for the case with CO_2 equilibrium in the pond. The relative saturation of $CaCO_3$ in the fly ash slurry increased from 29.3 to 89.1.

TABLE 3-3. EFFECTS OF MAKEUP WATER QUALITY ON TREATMENT REQUIRED FOR CLOSED-LOOP ASH SLUICING OF MONTOUR ASH*

Makeup Source	River Water	8-Cycle Cooling Tower Blowdown	20-Cycle Cooling Tower Blowdown
MAKEUP WATER COMPOSITION, mg/ℓ			
Calcium	28.	227.	567.
Magnesium	5.5	44.	110.
Sodium	8.0	65.	161.
Chloride	22.	176.	440.
Carbonate (as $CO_3^=$)	6.0	30.	23.
Sulfate (as $SO_4^=$)	68.	555.	1430.
Nitrate (as $NO_3^=$)	5.5	44.	110.
SLIPSTREAM TREATMENT RATE, ℓ/sec	38.5	43.7	50.8
% OF POND RECYCLE TREATED	27.	30.	36.
CALCIUM REMOVAL RATE, gmole/sec	0.88	1.06	1.36
FLY ASH SLURRY LIQUOR, mg/ℓ			
Calcium	500.	500.	510.
Magnesium	77.	120.	135.
Sodium	1150.	1420.	1940.
Chloride	22.8	180.	455.
Carbonate (as $CO_3^=$)	1.4	4.2	3.3
Sulfate (as $SO_4^=$)	3840.	4350.	5060.
Nitrate (as NO_3^-)	5.7	45.4	114.
pH	10.3	10.1	10.3
RELATIVE SATURATIONS**			
$CaCO_3$	0.97	2.4	1.7
$CaSO_4 \cdot 2H_2O$	1.06	1.07	1.08

*Based on ash reactivity determined from beaker leaching studies (worst case): no CO_2 transfer allowed in the pond.

**Critical values, above which scale potential exists, are 1.3-1.4 for $CaSO_4 \cdot 2H_2O$ and about 2.5 for $CaCO_3$ (see Appendix C)

TABLE 3-4. EFFECTS OF CO_2 TRANSFER IN POND ON FLY ASH SLURRY SCALING TENDENCY (BENCH-SCALE RESULTS)

	(Colstrip Ash)	
	No CO_2 Transfer	CO_2 Bubbled in Pond
POND LIQUOR, mg/ℓ		
Calcium	1240.	481.
Magnesium	0.*	0.*
Sodium	27.6	52.9
Chloride	39.1	31.2
Carbonate (as $CO_3^=$)	2.4	654.
Sulfate (as $SO_4^=$)	595.	566.
Nitrate (as NO_3^-)	14.3	12.4
pH	12.6	7.6
Relative Saturations		
$CaCO_3$	3.7	12.6
$Mg(OH)_2$	--	--
$CaSO_4 \cdot 2H_2O$	0.5	0.4
FLY ASH SLURRY, mg/ℓ		
Calcium	1000.	441.
Magnesium	0.*	0.*
Sodium	27.6	25.3
Chloride	39.1	29.1
Carbonate (as $CO_3^=$)	4.8	21.0
Sulfate (as $SO_4^=$)	691.	614.
Nitrate (as NO_3^-)	14.3	14.3
pH	12.6	11.7
Relative Saturations**		
$CaCO_3$	7.8	31.8
$Mg(OH)_2$	--	--
$CaSO_4 \cdot 2H_2O$	0.5	0.4
$CaCO_3$ PRECIPITATION RATE ACROSS MIX TANK, mmole/min	0.0	2.7

*Magnesium levels were not detectable due to the high pH's in the system ($Mg(OH)_2$ precipitation removed virtually all of the liquid phase magnesium from the system or prevented the dissolution of magnesium from the ash).

**Critical values, above which scale potential exists, are 1.3-1.4 for $CaSO_4 \cdot 2H_2O$, about 2.5 for $CaCO_3$, and about 3.4 for $Mg(OH)_2$ (see Appendix C)

TABLE 3-5. EFFECTS OF CO_2 TRANSFER IN POND ON FLY ASH SLURRY SCALING TENDENCY (COMPUTER MODEL RESULTS)

	(Bowen Ash)	
	No CO_2 Transfer	CO_2 Equilibrium with Air in Pond
POND LIQUOR, mg/ℓ		
Calcium	1170.	570.
Magnesium	.01	28.
Sodium	187.	188.
Chloride	33.	33.
Carbonate (as $CO_3^=$)	0.7	33.
Sulfate (as $SO_4^=$)	1290.	1740.
Nitrate (as NO_3^-)	67.	66.
pH	12.5	7.9
Relative Saturations		
$CaCO_3$	1.0	1.0
$Mg(OH)_2$	1.0	9.3×10^{-6}
$CaSO_4 \cdot 2H_2O$	1.0	1.0
FLY ASH SLURRY, mg/ℓ		
Calcium	1410.	1050.
Magnesium	11.	28.
Sodium	187.	187.
Chloride	33.	33.
Carbonate (as $CO_3^=$)	9.0	29.
Sulfate (as $SO_4^=$)	1850.	2130.
Nitrate (as NO_3^-)	67.	67.
pH	11.7	11.3
Relative Saturations**		
$CaCO_3$	29.3	89.1
$Mg(OH)_2$***	1460.	1200.
$CaSO_4 \cdot 2H_2O$	1.3	1.3
$CaCO_3$ SOLIDS FORMED IN SYSTEM, gmole/sec	.032	1.85

*Equilibrium partial pressure of CO_2 in pond specified to be equal to that in the atmosphere (3.3×10^{-4} atm).

**Critical values, above which scale potential exists, are 1.3-1.4 for $CaSO_4 \cdot 2H_2O$, about 2.5 for $CaCO_3$, and about 3.4 for $Mg(OH)_2$ (see Appendix C)

***Solid precipitation was not allowed. Kinetic studies (Appendix C) indicate that at these relative saturations, the magnesium will precipitate, resulting in very low magnesium concentrations in the liquid phase.

These cases represent the two extremes of what may actually happen in a plant situation. The samples taken at the plants studied in this program indicate that some CO_2 transfer occurs in the pond but complete equilibrium is not always achieved. At Bowen the partial pressure of CO_2 was 2×10^{-7} atm and at Montour the partial pressure was slightly above the equilibrium value of 3.3×10^{-4} atm. The degree of CO_2 transfer at a specific location will have a significant effect on the $CaCO_2$ relative saturation in the pond recycle and fly ash slurry liquors.

3.2.4 Degree of Recycle

The previous discussions have considered completely closed-loop ash siuicing operations and the effects of various operating parameters on these systems. However, in some cases completely closed-loop operation may not be desired and treatment steps might be eliminated. For example, if ash pond overflow is used as makeup to a scrubbing system, the ash sluicing network would be only partially closed-loop since a blowdown stream to a scrubber is used. Table 3-6 presents two computer simulation cases for a sluicing system using Montour ash. In the first case (column one) closed-loop operation is employed so that all of the pond overflow liquor is recycled to the system. A slipstream is taken from the pond recycle to remove calcium and control gypsum scale potential in the fly ash slurry. A slipstream treatment rate of about 77 ℓ/sec was required.

In the second case, gypsum scale potential is controlled by taking a blowdown stream from the system to keep the sulfate level low enough in the circulating liquor to prevent gypsum supersaturation. A blowdown rate of approximately 51 ℓ/sec was required to maintain a gypsum relative saturation near 1.0 in the fly ash slurry liquor. This corresponds to about 18% of the pond recycle liquor.

3.3 Recycle/Reuse Alternatives in Ash Sluicing Systems

Of the ash sluicing systems encountered, recirculation of the ash pond water was only practiced with bottom ash which is in general much less reactive. Both of the plants which sluice fly ash do so on a once-through basis. These studies revealed that a recirculating fly ash system may be employed but treatment may be necessary to prevent gypsum scale formation. The amount of leachable species in the ash and makeup water quality are the major parameters which determine the level of treatment necessary.

TABLE 3-6. EFFECTS OF DEGREE OF RECYCLE IN AN ASH SLUICING SYSTEM USING MONTOUR ASH*

	Closed-Loop Operation	Blowdown Taken from System
Fly Ash Rate, kg/hr	62,200	62,200
(lb/hr)	(137,000)	(137,000)
Pond Recycle Rate to Fly Ash Sluice, ℓ/sec	284	284
(GPM)	(4,500)	(4,500)
Sluice Water Makeup Rate, ℓ/sec	37.8	44.2
(GPM)	(600)	(1,400)
Pond Overflow Rate, ℓ/sec	0.0	51.1
(GPM)	(0.0)	(800)
Slipstream Treatment Rate,** ℓ/sec	77.0	0.0
(GPM)	(1,220)	(0.0)
Fly Ash Slurry, mg/ℓ		
Calcium	500	624
Magnesium	77	37
Sodium	1,150	8.2
Chloride	22.8	22.4
Carbonate (as $CO_3^=$)	1.4	2.2
Sulfate (as $SO_4^=$)	3,840.	1,600.
Nitrate (as NO_3^-)	5.7	5.6
pH	10.3	10.3
Relative Saturations***		
$CaCO_3$	0.97	3.3
$CaSO_4 \cdot 2H_2O$	1.06	1.0

*Based on ash reactivity from ash leaching experiments (worst case); no CO_2 transfer in the pond.

**Based on treatment to 50 mg/ℓ Ca to account for inefficiencies.

***Critical values, above which scale potential exists, are 1.3-1.4 for $CaSO_4 \cdot 2H_2O$, and about 2.5 for $CaCO_3$ (see Appendix C)

Determining the quantity of leachable species in different ashes is a difficult task in that the amount leached depends on liquor pH and composition. Bench-scale experiments revealed that solutions containing more dissolved species leach less of the ash than solutions with lower dissolved solids concentration. The leaching studies showed the variability in ash compositions and the pH dependency of the soluble species in fly ash. The results of the leaching studies represent the maximum levels of soluble species in each ash studied and were therefore used to represent "worst case" operation. Pilot or additional bench-scale studies are recommended to determine more accurately the solubility characteristics of a particular ash before a recirculating fly ash sluice system is implemented.

Carbon dioxide mass transfer between the pond liquor and the atmosphere will affect the $CaCO_3$ and $Mg(OH)_2$ scale potential in a fly ash sluice system. Increased CO_2 sorption in the pond will increase $CaCO_3$ scale potential and decrease $Mg(OH)_2$ scale potential. Since these scales are pH dependent (higher pH means more scale potential) problems may be encountered with very alkaline ashes. However, these scales are typically softer than gypsum scale and may be eroded by the ash. Installing reaction vessels prior to the fly ash slurry line may allow precipitation of these solids in a controlled fashion so that scale formation in the slurry line may be minimized. Again, pilot or bench-scale studies are recommended to more accurately quantify $CaCO_3$ and/or $Mg(OH)_2$ scale potential for a particular ash before a recirculating system is implemented.

4.0 SO_2/PARTICULATE SCRUBBING SYSTEMS

The third type of major water consumer encountered at the plants studied in this program is combined particulate and SO_2 scrubbing. Of the five plants investigated, two had scrubbing systems. The Four Corners Plant of Arizona Public Service has venturi particulate scrubbers on three of the five generating units although some SO_2 removal is also obtained. The Colstrip Plant of Montana Power Co. has combined SO_2 and particulate scrubbers on both of the generating units. Venturi collectors for particulate removal are followed by spray chambers for SO_2 removal.

This section of the report first presents a typical scrubbing process flow scheme including discussions of differences between the typical system and actual systems studied. The process description is followed by discussions of the various operating parameters and their effects on the design and operation of scrubbing systems. The final portion of this section discusses the potential for scrubbing in various recycle/reuse alternatives at power plants. Since most scrubbing systems are designed for zero discharge, they may possibly be used as receptors for the final water effluent in a cascaded water system to achieve zero discharge or reduced blowdown for an entire plant water network.

4.1 Process Description

A typical scrubbing system may be divided into three major operations:

1) gas cleaning,
2) solids precipitation, and
3) solids concentration.

The combination of these operations is shown in the simplified scrubbing system in Figure 4-1. Gas cleaning is accomplished in the scrubber vessel, solids precipitation occurs in the reaction tank, and solids concentration is achieved in the solid-liquid separator which may be a clarifier, filter, pond, or any combination of the three. This section presents a discussion of each of these major operations observed in scrubbing systems and how the two specific systems studied deviate from the typical flow scheme in Figure 4-1. More detailed discussions of the scrubbing systems at Four Corners and Colstrip may be found in Appendices F and J, respectively.

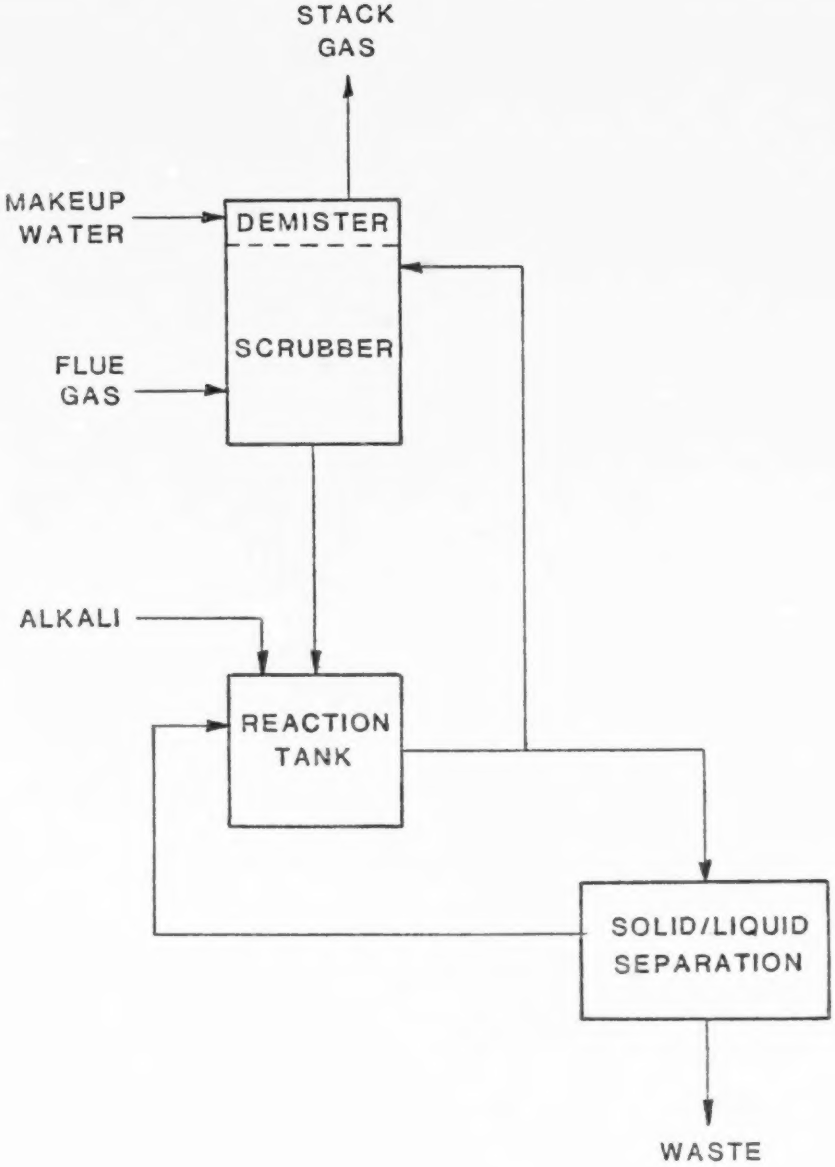

STACK GAS
MAKEUP WATER
DEMISTER
SCRUBBER
FLUE GAS
ALKALI
REACTION TANK
SOLID/LIQUID SEPARATION
WASTE

Figure 4-1. Typical scrubbing system flow scheme.

4.1.1 Gas Cleaning

In both particulate and combined SO_2/particulate scrubbing systems, the boiler flue gas is contacted with a recirculated slurry in the scrubber vessel where the particulates (fly ash) and/or SO_2 are absorbed. Venturi scrubbers are used for particulate removal at both Four Corners and Colstrip. However, at Colstrip where the scrubbers are designed for combined particulate and SO_2 removal, the venturi sections are followed by spray sections where most of the SO_2 is absorbed.

Spray towers provide more liquid-gas contact area and longer residence times than venturis and are therefore more efficient at removing SO_2 from the flue gas. At Four Corners only about 30% of the SO_2 in the flue gas is removed in the venturis, but at Colstrip 74% of the scrubber inlet SO_2 is removed by the combination of venturi and spray sections.

To prevent excess carryover of the scrubbing liquor with the clean gas, mist eliminators are used in the scrubbers. The mist eliminators are generally washed with fresh makeup water which falls into the scrubber after being sprayed over the demisters. At Colstrip, a wash tray collects some of the wash water so that it may be reused along with the makeup water as demister wash.

4.1.2 Solids Precipitation

The second major operation in scrubbing systems is solids precipitation. In a lime or limestone based closed-loop scrubbing system, the SO_2 which is absorbed must be removed from the system by precipitation of calcium sulfate and calcium sulfite. The required rate of precipitation is determined by the rate of absorption of SO_2 from the flue gas. At both Four Corners and Colstrip, greater than 90% of the sulfite formed in the liquid phase by SO_2 sorption is oxidized to sulfate, making the precipitation of gypsum ($CaSO_4 \cdot 2H_2O$) the controlling rate of solids formation.

It should be noted that revision of system operation could alter the sulfite oxidation rate significantly. Systems with lower than approximately 15% oxidation can be designed for the so-called "subsaturated gypsum mode" whereby the calcium sulfate coprecipitates with calcium sulfite. The results presented here assume high (>90%) sulfite oxidations.

The precipitation of the absorbed sulfur occurs in a reaction tank where adequate time is allowed for crystal growth of recirculated calcium sulfate and calcium sulfite particles. If the residence time of the reaction tank is too small, then the concentrations of sulfate and sulfite will increase until nucleation occurs, resulting in scale formation. The scale will most likely form in the scrubber where sulfur concentrations are highest.

At Four Corners, where scaling has been noted, the reaction time for solids precipitation is very small (about one minute), whereas at Colstrip the reaction tank residence time is about eight minutes. No scaling has been reported for the Colstrip scrubbing system. The effects of reaction tank volume on system operation will be quantified in Section 4.2 which discusses process variables.

The sorbed fly ash solids and precipitated sulfur solids must be removed from the recirculating slurry at a rate sufficient to control the solids concentration in the circulating slurry at the desired level. At Colstrip, the blowdown is taken at a rate sufficient to keep the circulating solids concentration at about 12%. At Four Corners, the circulating solids concentration is about 2%. The low value of 2% is used at Four Corners to minimize erosion problems. Higher solids concentrations are more abrasive but require smaller reaction tanks due to the increased number of precipitation sites. The blowdown from the recirculating slurry is pumped to the solid/liquid separation portion of the system.

4.1.3 Solid/Liquid Separation

In order to minimize water requirements for a scrubbing system, solid/liquid separation is employed to recover a portion of the water used to slurry the waste solids (ash, $CaSO_4 \cdot 2H_2O$, $CaSO_3 \cdot \frac{1}{2}H_2O$). Higher percent solids also allow for easier disposal of the sludge as landfill. This separated water can be recycled to the scrubbing system to eliminate any aqueous discharge and reduce makeup water requirements. The final sludge water content and the evaporation occurring in the scrubber determine the makeup water requirements for the system.

Typical solid/liquid separation techniques include clarification, filtration, and ponding or combinations of these techniques. At Four Corners the 2% solids slurry blowdown is clarified to about 10% solids (typical operation) and pumped to a pond. The clarifier overflow is returned to the scrubbing system. In the ash pond, the sludge settles to about 50% water and the excess water (not evaporated or occluded with sludge) is discharged rather than recirculated.

In the Colstrip scrubbing system, the 12% solids stream is diluted to about 6% solids with pond water and pumped to the scrubber ponds where the solids (ash and $CaSO_4 \cdot 2H_2O$, predominantly) settle to about 50% water. The remaining water which is not evaporated is recycled to the scrubbing system.

4.2 Process Variables

The effects of important process variables concerning scale control were investigated as well as the effects on makeup water requirements for the two scrubbing systems studied using the computer models discussed in Appendix E. The parameters affecting the system water makeup requirements are SO_2 removal rate, ash removal rate, and pond recycle rate. Other parameters considered include liquid-to-gas ratio, circulating slurry solids concentration, reaction tank volume, and makeup water quality. The following sections contain quantitative evaluations of the effects of these parameters on the operation of particulate and SO_2 scrubbing systems. Detailed analyses of the Four Corners and Colstrip scrubbing operations are presented in Appendices F and J, respectively.

The scrubbing models used in this study calculate all stream compositions and flow rates in the system using precipitation rate kinetics for $CaSO_4 \cdot 2H_2O$ and $CaSO_3 \cdot \frac{1}{2}H_2O$, which are the solids formed in lime/limestone scrubbing systems, and various input parameters. These parameters characterize the operating conditions for a particular scrubbing system and include flue gas flow and composition, fly ash rate and composition, makeup water composition, lime addition rate, tank volumes, scrubber feed flow rate and percent suspended solids, percent oxidation in the system, and percent solids in the sludge.

Iterative calculations are performed around the scrubbing loop through the scrubber vessel and the scrubber recycle tank (if applicable) until relative saturations and stream compositions satisfy the rate equations. The calculations are performed for ancillary equipment such as the reheat and fan requirements, and to determine additional stream compositions. Makeup water requirements are calculated by an overall system balance.

Several assumptions are inherent in performing scrubber simulations with the model outlined above. These are enumberated below:

1) The scrubber exit gas is saturated with respect to water.
2) Equilibrium exists between CO_2 in the stack gas and liquor in the scrubber bottoms.
3) The scrubber bottoms and stack gas temperatures are the adiabatic saturation temperature of the flue gas.
4) All oxidation was assumed to occur in the scrubber.
5) All solids precipitation occurs in reaction vessels.

4.2.1 SO_2 Removal Rate

The effect of SO_2 removal rate on scrubber makeup water requirements may be determined by examining the results of two of the Four Corners process simulations. In the high solids operations case where the circulating solids concentration is 9%, the clarifier underflow is 30% and the final slurry discharged is 17%, only 30% SO_2 removal is specified. 50% SO_2 removal was specified for Alternative Two. This alternative mode of operation is with 10% solids in the circulating liquor and 30% solids in the final slurry discharged. Table 4-1 presents the characteristics of the solid waste for each of these cases as well as the operating conditions and makeup water requirements.

Direct comparison of the makeup water requirements for these two cases as a function of SO_2 removal cannot be made since the waste suspended solids concentrations are different. Table 4-1 shows an adjusted makeup water rate based on the solids flow in the waste and a solids concentration of 30% in the waste for both cases. The difference in adjusted makeup water requirements is only 2.1 ℓ/sec or about 3% of the total makeup for a change in SO_2 removal from 30% to 50%.

This effect is small due in part to the ash comprising more than 90% of the solids in the waste. Although the amount of sulfate solids changed considerably, the overall impact is small, since the sulfate solids represent less than 10% of the total

TABLE 4-1. EFFECTS OF SO_2 REMOVAL RATE ON FOUR CORNERS SCRUBBER MAKEUP REQUIREMENTS

	High Solids Operations	Alternative Two
SO_2 in Flue Gas, ppm	640.	640.
Ash in Flue Gas, g/sec (lb/min)	16,200. (2140)	16,200. (2140)
SO_2 Removal, %	30.	50.
Particulate Removal, %	99.7	99.7
Final Slurry to Ash Pond		
Wt. % Solids	17.3	30.
Solids Composition, Wt. %		
$CaSO_4 \cdot 2H_2O$	3.9	7.9
Inert (Ash)	96.1	92.1
Solids Flow, g/sec (lb/min)	16,600. (2200)	17,500. (2300)
Makeup Water Requirements, ℓ/sec (GPM)		
Evaporation	30.0 (475)	30.0 (475)
Occluded with Solids	79.0 (1250)	40.7 (645)
Total	109.0 (1735)	70.7 (1120)
Makeup Water Rate Adjusted to 30% Solids in Waste, ℓ/sec (GPM)		
Evaporation	30.0 (475)	30.0 (475)
Occluded with Solids	38.6 (612)	40.7 (645)
Total	68.6 (1087)	70.7 (1120)

solids. The total amount of solids changed only by about 5%. As the amount of sulfur removed in relationship to the ash removed increases, the effects of SO_2 removal on makeup water requirements will become more pronounced.

The effect of changes in SO_2 removal rate on makeup water rate will be dampened by the fact that water evaporation in the scrubber frequently represents a major portion of the makeup water requirement. As the evaporation becomes a larger part of the makeup water, changes in SO_2 removal rate will have a decreasing effect on the overall scrubber makeup rate. At Four Corners, for the high solids operation case (17% solids in final waste), the evaporation is about 30% of the total makeup. However, at Colstrip the evaporation is about 80% of the total makeup because the final sludge solids concentration is about 50%, and only a small amount of water is lost with the solids.

4.2.2 Ash Removal Rate

The effect of the ash removal rate on makeup water requirements for combined SO_2 and particulate scrubbing is more pronounced than that of the SO_2 removal rate in the situations studied. The scrubbing situations encountered were for low sulfur applications. In the cases studied, most of the solid waste was ash as opposed to calcium sulfate or calcium sulfite.

As the ash removal rate is decreased, by burning a coal of lower ash content or by decreasing load for example, the makeup water requirements for the scrubbing system are decreased since less water is lost from the system by occlusion with the solids. By an overall mass balance around the scrubbing system, the makeup water rate may be calculated by Equation 4.1:

$$M = E + \frac{A(1 - X_D)}{\rho_L X_A X_S} (1 - X_S) \qquad (4.1)$$

where

M = makeup water requirement, ℓ/sec

E = evaporation (scrubber + pond), ℓ/sec

A = ash removal rate, g/sec

ρ_L = density of water, g/ℓ

X_D = weight fraction of ash which is soluble

X_A = weight fraction of solids in waste which is ash

X_S = weight fraction solids in waste stream

The makeup water requirement is the sum of two components. One is the evaporation in the scrubber and the other is the water occluded with the solids in the waste stream. The second term in Equation 4.1 represents the water lost with the solid waste and is directly proportional to the ash removal rate, A. Table 4-2 presents data from two scrubbing simulations for the Four Corners Plant and two for the Colstrip Plant which illustrate the effects of flue gas ash content on scrubbing system makeup water requirements. The two cases for Four Corners represent a reduction in flue gas ash content of 60%, from 16,200 g/sec to 6,480 g/sec. The water lost through solids occlusion was reduced from 17.5 ℓ/sec to 8.0 ℓ/sec resulting in an overall makeup water reduction of about 20% from 50.7 ℓ/sec to 41.2 ℓ/sec.

Lowering the ash removal rate did not produce a proportional reduction in water lost with the solids since the fraction of ash in the solids also decreased. From Equation 4.1, lowering the fraction of ash in the solids, X_A, will increase the makeup water requirements. A directly proportional decrease of occluded water would have been to 7.0 ℓ/sec insteam of the 8.0 ℓ/sec calculated. This difference is due to X_A changing as well as A, the ash removal rate, in Equation 4.1.

The two simulated cases for the Colstrip scrubbing system produced similar results in that a 30% reduction in ash removal rate caused only a 14% reduction in occluded water. Again, this is due to the change in the solids composition. The weight fraction of ash in the solids decreased from 0.568 to 0.474 for these two cases. Overall makeup water requirements were reduced by only about 2%, from 58.2 ℓ/sec to 57.1 ℓ/sec, since most of the makeup water requirements are needed to replace evaporated water rather than occluded water.

The ash removal rate will also affect the scaling tendencies in the system. A decrease in ash removal rate will increase the amount of calcium sulfite and calcium sulfate solids being recirculated. This provides more crystal sites for precipitation and therefore decreases the tendency of the system to form scale. For example, comparison of the reaction tank liquors for the two Colstrip simulations shown in Table 4-3 shows a decrease in calcium sulfate relative saturation from 1.41 to 1.37 when the amount of ash removed is decreased from 5500 g/sec to 3800 g/sec.

TABLE 4-2. EFFECTS OF ASH REMOVAL RATE ON SCRUBBER MAKEUP REQUIREMENTS

	Four Corners		Colstrip	
	Alternative* Three	Alternative** Four	Design Conditions	Low Ash Conditions
Ash in Flue Gas, g/sec (lb/min)	16,200. (2140)	6480. (860)	5500. (730)	3800. (500)
Particulate Removal, %	99.7	99.7	99.6	99.6
Total Fraction of Ash Dissolving	.011	.011	.193	.193
SO_2 in Flue Gas, ppm	640.	640.	790.	790.
SO_2 Removal, %	50.	50.	74.	74.
Solid Waste				
Wt. % solids	50.	50.	50.	50.
Solid Composition, wt. %				
$CaSO_3 \cdot \frac{1}{2}H_2O$	--	--	4.1	5.2
$CaSO_4 \cdot 2H_2O$	8.5	18.8	39.0	47.4
Inert (Ash)	91.5	81.2	56.8	47.4
Solids Flow, g/sec (lb/min)	17,500. (2300)	8000. (1060)	7740. (1020)	6560. (870)
Makeup Water Requirement, ℓ/sec (GPM)				
Evaporation	33.2 (525)	33.2 (525)	50.5 (800)	50.5 (800)
Solids Occlusion	17.5 (278)	8.0 (127)	7.7 (122)	6.6 (105)
Total	50.7 (803)	41.2 (652)	58.2 (922)	57.1 (905)

*Repiped scrubber system with adequate reaction tank volume to prevent scale and recycle of ash pond overflow.

**Same as Alternative Three except ash content of flue gas lowered by 60%.

TABLE 4-3. EFFECT OF ASH REMOVAL RATE ON COLSTRIP SCRUBBING SYSTEM SCALING TENDENCY

	Design Conditions	Low Ash Conditions
Ash in Flue Gas, g/sec (lb/min)	5,500. (730)	3,800. (500)
Scrubber Recycle Slurry		
pH	5.0	5.2
Liquor Composition, mg/ℓ		
Calcium	733.	715.
Magnesium	5,285.	4,267.
Sodium	444.	448.
Chloride	117.	132.
Carbonates (as $CO_3^=$)	153.	156.
Sulfates (as $SO_4^=$)	21,000.	17,800.
Sulfites (as $SO_3^=$)	3,560.	2,135.
Nitrates (as NO_3^-)	9.6	10.9
$CaSO_4 \cdot 2H_2O$ Relative Saturation*	1.41	1.37
Solid Composition, wt. %		
$CaSO_4 \cdot 2H_2O$	38.9	47.2
Inert (Ash)	57.3	47.8
$CaSO_3 \cdot \frac{1}{2}H_2O$	3.8	5.0

*The critical value, above which scale potential exists, is 1.3-1.4 for $CaSO_4 \cdot 2H_2O$.

4.2.3 Ash Pond Recycle Rate

Although most throwaway scrubbing systems are designed for closed-loop operation (no aqueous discharges) some systems may operate with a blowdown from time to time. This section describes the impact on the scrubbing system water balance of operation with or without recycle of ash pond overflow. The Four Corners scrubbing system simulations chosen to quantify the effects of ash pond recycle are summarized in Table 4-4. Detailed operating data and simulation results may be found in Appendix F.

The first column of Table 4-4 (Alternative Two) represents operation of the system with a solid waste suspended solids concentration of 30%. No pond water is recycled to the system in this case. Alternative Three represents identical conditions except the ash pond water is recycled to the reaction tank after the waste solids have settled to 50% water. The solids composition was changed slightly due to changes in the liquid composition in the system, resulting from the recycle of the pond water. The major influence on the makeup water rate, however, was the change in solids concentration in the final waste from 30% in Alternative Two to 50% for Alternative Three. The occluded water decreased from 40.7 ℓ/sec to 17.5 ℓ/sec to reduce the overall makeup requirements from 70.7 ℓ/sec to 50.7 ℓ/sec. The evaporation component of the makeup water requirements increased slightly in Alternative Three due to the evaporation occurring in the ash pond.

Recycle of the ash pond liquor, in addition to decreasing makeup water requirements, raises the dissolved solids level in the scrubbing system. The effect on the system scaling tendency is illustrated by the two simulation cases presented in Table 4-5. The calcium sulfate relative saturation of the scrubber liquor remains unchanged at 1.07 for both cases although the TDS increases from 4,000 to 5,200 mg/ℓ. Therefore, with adequate reaction time, recycle of the ash pond overflow to the reaction vessel will not cause scaling problems. The total dissolved solids concentration increases, however, from about 4,000 mg/ℓ to about 5,200 mg/ℓ.

4.2.4 Slurry Solids Concentration

The scrubber makeup requirements are not affected by the recirculating slurry solids content but a study of water recycle/reuse opportunities in scrubbing systems necessitates an understanding of scaling and the parameters which may be used to control scaling potential. The recirculating solids concentration will have a significant impact on the scale potential in the system

TABLE 4-4. EFFECT OF POND RECYCLE ON FOUR CORNERS SCRUBBER MAKEUP REQUIREMENTS

	Alternative Two*	Alternative Three**
Ash in Flue Gas, g/sec (lb/min)	16,200. (2140)	16,200. (2140)
Particulate Removal, %	99.7	99.7
Total Fraction of Ash Dissolving	.011	.011
SO_2 in Flue Gas, ppm	640.	640.
SO_2 Removal, %	50.	50.
Solid Waste		
Wt. % Solids	30.	50.
Solid Composition, Wt. %		
$CaSO_4 \cdot 2H_2O$	7.9	8.5
Inert (Ash)	92.1	91.5
Solid Flow, g/sec (lb/min)	17,500. (2300)	17,500. (2300)
Pond Recycle Rate, ℓ/sec (GPM)	0.0 (0)	20.0 (320)
Makeup Water Requirement, ℓ/sec (GPM)		
Evaporation	30.0 (475)	33.2 (525)
Solids Occlusion	40.7 (645)	17.5 (278)
Total	70.7 (1120)	50.7 (803)

*Repiped scrubbing system with adequate reaction time to prevent scale, no ash pond recycle.

**Same as Alternative Two except all ash pond overflow is recycled.

TABLE 4-5. EFFECT OF ASH POND RECYCLE ON FOUR CORNERS SCRUBBING SYSTEM SCALING TENDENCY

	Alternative Two*	Alternative Three**
Pond Recycle Rate, ℓ/sec (GPM)	0.0 (0)	20.0 (320)
Solid Waste Solids Concentration, wt. %	30.	50.
Scrubber Recycle Slurry		
pH	6.9	7.0
Liquor Composition, mg/ℓ		
Calcium	670.	640.
Magnesium	84.	145.
Sodium	450.	790.
Chloride	235.	390.
Carbonates (as $CO_3^=$)	116.	105.
Sulfate (as $SO_4^=$)	2400.	3100.
Sulfite (as $SO_3^=$)	33.	35.
Nitrate (as NO_3^-)	16.	27.
TDS	4000.	5200.
$CaSO_4 \cdot 2H_2O$ Relative Saturation***	1.07	1.07
Solids Composition, wt. %		
$CaSO_4 \cdot 2H_2O$	7.9	8.1
Inert (Ash)	92.1	91.9

*Repiped system with adequate reaction time to prevent scale and no pond recycle.

**Same as Alternative Two except ash pond overflow is recycled.

***The critical value, above which scale potential exists, is 1.3-1.4 for $CaSO_4 \cdot 2H_2O$.

because the solids provide precipitation sites for $CaSO_3 \cdot \frac{1}{2}H_2O$ and $CaSO_4 \cdot 2H_2O$. A decrease in the number of sites slows precipitation rates and therefore maintains more calcium and sulfate in solution, raising the calcium sulfate relative saturation. This effect is illustrated by the two simulations of the Colstrip scrubbing system shown in Table 4-6. As the slurry solids concentration was reduced from 12.6% to 7.6%, the calcium sulfate relative saturation increased to 1.73, which is considerably above the critical range for scale formation of 1.3-1.4.

The recirculating slurry solids concentration is therefore an important parameter to control as far as scale prevention is concerned. A tradeoff does exist, though, in that slurries with higher solids concentrations are more abrasive.

4.2.5 Reaction Tank Size

In a lime or limestone based SO_2 scrubbing system, the control of $CaSO_4 \cdot 2H_2O$ and $CaSO_3 \cdot \frac{1}{2}H_2O$ scale potential is an extremely important consideration. If scaling conditions are realized for significant amounts of time in any part of the system, chemical scale will probably be deposited on equipment which will eventually necessitate system shutdown for cleaning. Pure phase calcium sulfite or calcium sulfate kinetics can be described by the expression:

$$R = KafCV\,(R.S. - 1) \qquad (4.2)$$

where

R = precipitation rate

K = temperature dependent constant

a = crystal interfacial area per mass of precipitating solid

f = weight fraction of the precipitating species in the solid phase

C = total solids concentration in the slurry

V = reaction tank volume

$R.S.$ = relative saturation of the precipitating species.

TABLE 4-6. EFFECT OF SLURRY SOLIDS CONCENTRATION ON COLSTRIP SCRUBBER SCALE POTENTIAL

Scrubber Recycle Slurry	Design Conditions	Low Solids
Suspended Solids, wt. %	12.6	7.6
pH	4.98	5.09
Liquor Composition, mg/ℓ		
Calcium	733.	897.
Magnesium	5,285.	5,590.
Sodium	444.	469.
Chloride	117.	124.
Carbonates (as $CO_3^=$)	153.	167.
Sulfate (as $SO_4^=$)	21,000.	22,300.
Sulfite (as $SO_3^=$)	3,560.	3,930.
Nitrate (as NO_3^-)	9.6	10.2
$CaSO_4 \cdot 2H_2O$ Relative Saturation*	1.41	1.73
Solid Composition, wt. %		
$CaSO_4 \cdot 2H_2O$	38.9	38.7
Inert (Ash)	57.3	57.9
$CaSO_3 \cdot \frac{1}{2}H_2O$	3.8	3.4

*The critical value, above which scale potential exists, is 1.3-1.4 for $CaSO_4 \cdot 2H_2O$.

The system precipitation rates are set by the SO_2 removal rate and oxidation rate. As can be seen from Equation 4.2, increases in the weight fraction of gypsum in the solid phase, the total solids concentration in the circulating slurry, or the reaction tank volume should decrease the gypsum relative saturation in the reaction tank for a specific precipitation rate. Table 4-7 illustrates the effect of reaction tank volume on relative saturation for the Four Corners scrubbing system.

The only difference between Cases One and Two of Alternative Three is the reaction tank volume. This alternative involved recycle of the ash pond overflow in a repiped system with adequate reaction tank volume for scale control. As the tank size was decreased from 37,500 m^3 to 21,200 m^3, the gypsum relative saturation in the tank increased from 1.07 to 1.13. The decrease in reaction time kept more calcium and sulfate in the liquid phase and less in the solid phase, resulting in the increase in relative saturation. The change in solid phase composition was very small and did not have a significant impact on the results. The change in relative saturation is only about 5% different from what would be expected by direct ratio using Equation 4.2 (neglecting changes in solid composition).

These results are based on the assumption that 98.6% of the sorbed SO_2 is oxidized. Four Corners scrubber tests performed by Arizona Public Service since this study was made indicate that the amount of sorbed SO_2 that is oxidized is a function of the pH of the scrubbing liquor. Lime addition in their venturi scrubbers at Four Corners raised the pH and reduced the oxidation to a level that permits operation in the "subsaturated gypsum mode". They found that the reaction tank volume required with reduced oxidation is significantly less than that predicted using the 98.6% oxidation assumption in the simulations.

4.2.6 Liquid-to-Gas Ratio

The effects of liquid-to-gas ratio (L/G) on the revised Four Corners scrubbing system operation are shown in Table 4-8. The simulation results shown in the first column (Alternative Two, Case One) represent operation at the present L/G at Four Corners (4.7 ℓ/m^3 @ STP) but with adequate reaction time for scale control. The calculated pH for the scrubber bottoms stream is 2.9. This low value could cause corrosion problems if the system operated in this manner for extended periods of time.

TABLE 4-7. EFFECT OF REACTION TANK VOLUME ON FOUR CORNERS SCRUBBING SYSTEM SCALING POTENTIAL

	Alternative Three Case One*	Alternative Three Case Two**
Combined Reaction Tank Volume***, m^3	37,500.	21,200.
(ft^3)	1.32×10^6	7.5×10^5
Scrubber Recycle Slurry		
Suspended Solids, wt. %	10.0	10.0
pH	7.0	7.0
Liquor Composition, mg/ℓ		
Calcium	640.	670.
Magnesium	145.	140.
Sodium	790.	760.
Chloride	390.	360.
Carbonate (as $CO_3^=$)	104.	93.
Sulfate (as $SO_4^=$)	3,110.	3,120.
Sulfite (as $SO_3^=$)	35.	40.
Nitrate (as NO_3^-)	27.	25.
$CaSO_4 \cdot 2H_2O$ Relative Saturation****	1.07	1.13
Solid Composition, wt. %		
$CaSO_4 \cdot 2H_2O$	8.0	7.9
Inert (Ash)	92.0	92.1
Flue Gas Ash Flow, g/sec	16,200.	16,200.
(lb/min)	(2140)	(2140)
SO_2 in Flue Gas, ppm	640.	640.
SO_2 Removal Rate, %	50.	50.
SO_2 Oxidation, %	98.6	98.6

*Repiped Scrubbing System, more than adequate reaction tank volume for scale control.

**Same as Case 1 but reduced reaction tank volume.

***Combined volume of all six proposed reaction tank vessels (one per scrubbing train).

****The critical value, above which scale potential exists, is 1.3-1.4 for $CaSO_4 \cdot 2H_2O$.

TABLE 4-8. EFFECTS OF LIQUID-TO-GAS RATIO ON FOUR CORNERS SCRUBBING OPERATION

	Alternative Two Case One*	Alternative Two Case Two**
Liquid-to-Gas Ratio, ℓ/m^3 @ STP	4.7	10.0
(gal/1000 ACF)	18.7	39.8
Scrubber Effluent Slurry		
Suspended Solids, wt. %	10.5	10.2
pH	2.9	3.9
Liquor Composition, mg/ℓ		
Calcium	700.	690.
Magnesium	85.	85.
Sodium	450.	450.
Chloride	240.	240.
Carbonate (as $CO_3^{=}$)	124.	120.
Sulfate (as $SO_4^{=}$)	2,750.	2,580.
Sulfite (as $SO_3^{=}$)	37.	35.
Nitrate (as NO_3^{-})	16.	16.
$CaSO_4 \cdot 2H_2O$ Relative Saturation ***	1.16	1.14
Solid Composition, wt. %		
$CaSO_4 \cdot 2H_2O$	7.4	7.6
Inert (Ash)	92.6	92.4
Flue Gas Ash Flow, g/sec	16,200.	16,200.
(lb/min)	(2140)	(2140)
SO_2 in Flue Gas, ppm	640.	640.
SO_2 Removal, %	50.	50.
SO_2 Oxidation, %	98.6	98.6

*Alternative Two involves repiping scrubbing system, adding reaction tank volume to control scale. Ash pond overflow is not recycled.

**Same as Case One except L/G increased.

***The critical value, above which scale potential exists, is 1.3-1.4 for $CaSO_4 \cdot 2H_2O$.

The second column in Table 4-8 presents the results from a simulation with a higher L/G of 10.0 ℓ/m^3 @ STP. The calculated pH of the scrubber effluent stream was 3.9 as opposed to the value of 2.9 for the previous case. This value is still not ideal from the standpoint of corrosion control but is somewhat better than the 2.9 pH scrubber liquor. The reason for the rise in pH from Case One to Case Two is that less SO_2 is absorbed per volume of scrubbing liquor so that the change in liquid phase sulfur concentration across the scrubber is less. This results in less of a pH drop across the scrubber. In both cases the scrubber feed pH was 6.9.

A small change in gypsum relative saturation in the scrubber effluent occurred with the increase in L/G (dropped from 1.16 to 1.14 when L/G increased from 4.7 ℓ/m^3 @ STP to 10.0 ℓ/m^3 @ STP). This again is due to the smaller sorption rate of SO_2 per volume of scrubber liquor and therefore a smaller change in relative saturation across the scrubber.

4.2.7 Makeup Water Quality

The effects of makeup water quality on scrubbing system operation and design were determined by using the Colstrip scrubbing system data and varying the makeup water composition input to the simulation model. Table 4-9 presents the results from three simulations where the makeup water composition was varied. The first case represents the design conditions with makeup water being softened river water. The other two cases represent using untreated river water and cooling tower blowdown as makeup water.

The results from these simulations indicate that the makeup water has very little effect on the recirculating slurry scaling tendency. The relative saturation of gypsum did not change appreciably between cases. The liquor composition did change considerably. The total dissolved solids concentrations ranged from 31,000 mg/ℓ for the base case to 46,000 mg/ℓ for the case using cooling tower blowdown as makeup.

The chloride content of the scrubbing liquor increased from 120 mg/ℓ for the base case to 1,560 mg/ℓ for the case where cooling tower blowdown is used. The corrosive properties of this liquor will depend on the materials of construction for the scrubber. The feasibility of use of cooling tower blowdown depends therefore in part on the chloride content of the initial makeup water to the plant. Higher chloride levels may cause corrosion problems in some scrubbing systems.

TABLE 4-9. EFFECTS OF MAKEUP WATER QUALITY ON COLSTRIP SCRUBBING SYSTEM SCALING POTENTIAL

	Case A	Case B	Case C
Makeup Water Source	Softened River Water	Raw River Water	Cooling Tower* Blowdown
Makeup Water Composition, mg/ℓ			
Calcium	39.9	57.9	534.
Magnesium	10.7	10.7	143.
Sodium	40.3	40.3	540.
Chloride	17.0	48.7	227.
Carbonate (as $CO_3^{=}$)	6.0	17.3	6.5
Sulfate (as $SO_4^{=}$)	188.	188.	2,640.
Nitrate (as NO_3^{-})	1.4	1.7	18.7
Scrubber Recycle Slurry			
Suspended Solids, wt. %	12.6	12.6	12.6
pH	5.0	5.0	5.0
Liquor Composition, mg/ℓ			
Calcium	730.	740.	690.
Magnesium	5,290.	5,280.	6,190.
Sodium	440.	440.	3,870.
Chloride	120.	330.	1,560.
Carbonate (as $CO_3^{=}$)	150.	150.	150.
Sulfate (as $SO_4^{=}$)	21,000.	20,700.	29,400.
Sulfite (as $SO_3^{=}$)	3,560.	3,550.	3,700.
Nitrate (as NO_3^{-})	10.0	12.0	130.
TDS	31,000.	31,000.	46,000.
$CaSO_4 \cdot 2H_2O$ Relative Saturation**	1.41	1.41	1.42
Solid Composition, wt. %			
$CaSO_4 \cdot 2H_2O$	38.9	38.9	39.9
Inert (Ash)	57.3	57.2	56.3
$CaSO_3 \cdot \frac{1}{2}H_2O$	3.8	3.9	3.8

*Use of this water as demister wash may not be feasible depending on the amount of SO_2 sorbed in the demister.

**The critical value, above which scale potential exists, is 1.3-1.4 for $CaSO_4 \cdot 2H_2O$.

Since scrubbing systems generally use makeup water as demister wash, the use of cooling tower blowdown may be limited to other makeup requirements such as pump seal water. The feasibility of using cooling tower blowdown as demister wash will depend on the amount of SO_2 sorbed in the demisters. Since cooling tower blowdown may be nearly saturated with respect to $CaSO_4 \cdot 2H_2O$ when maximum cycles of concentration is achieved in the tower system, only a small amount of SO_2 sorbed in the demisters may cause scaling problems. Colstrip pilot studies indicated that cooling tower blowdown could not be used as demister wash in that system.

One possible solution to this problem is to dilute the cooling tower blowdown with a subsaturated stream such as river water so that when SO_2 is absorbed, the critical relative saturation of $CaSO_4 \cdot 2H_2O$ will not be exceeded in the demisters. Pilot studies to determine the required dilution under various operating conditions are needed before a system change to an existing scrubbine process could be made.

4.3 Recycle/Reuse Alternatives in SO_2/Particulate Scrubbing Systems

Makeup water is required in SO_2/particulate scrubbing systems to replace water lost through evaporation and through occlusion with the waste solids. Evaporative losses include evaporation in the scrubber, from process vessels, and in the pond system if the pond overflow is recycled to the scrubbers. These losses are fixed by the flue gas flow, temperature, and water content and by the exposed area of process vessels and the pond system.

The amount of water lost through solids occlusion depends on the amount of solids produced and the weight fraction solids of the waste. Scrubbing systems may be designed to be closed loop, i.e., no aqueous discharges. The Four Corners study (Appendix F) showed that recycle of the ash pond overflow liquor had no appreciable effect on the recirculating slurry scaling potential. In this case, where a pond is used for disposal, the final sludge composition will be approximately 50% solids (1 kg of water lost per kg of solids).

The amount of solids to be disposed of will depend on the ash removal rate and the SO_2 removal rate. The relative amount of ash and SO_2 will determine which removal rate has the most effect on the amount of solids produced. At Four Corners, where about 30 kg of ash are removed per kg of SO_2, the SO_2 removal rate has very little effect on the scrubber makeup requirements.

Since scrubbers can be operated in a closed-loop fashion, there is little opportunity for recycle/reuse but they can be used as a sink for water streams which might normally be discharged from a power plant such as cooling tower blowdown. The use of various qualities of makeup water did not affect the scaling potential of the scrubber recycle liquor in the Colstrip scrubbing simulations (Appendix J). This indicates that the quality of makeup water not used as demister wash (for instance, pump seal water) does not have a major impact on scrubber scaling tendency. The composition of this water will, however, affect the chloride content of the recirculating liquor. Corrosion problems could possibly occur if the chloride content of the makeup water is too high.

The use of water which is saturated or near-saturated with respect to gypsum (such as cooling tower blowdown) as demister wash is not recommended since the addition of small amounts of SO_2 in the demister may cause scale formation. Combining cooling tower blowdown with fresh makeup water and using this mix as demister wash may be feasible in some situations. A careful process analysis and pilot studies are suggested for determining the quality of water required for demister wash in a particular scrubbing system.

5.0 COMBINED SYSTEMS

The object of this study was to evaluate methods to minimize the aqueous discharges and makeup requirements for coal-fired steam-electric generating stations. In Sections 2.0, 3.0, and 4.0, the operating conditions of the major water consumers at power plants were discussed. In these sections, methods to reduce the water consumption of the individual processes were presented. It is important to use these methods in an efficient combination to produce an overall system which will reduce the discharge requirements of the entire plant at a reasonable cost. This section discusses alternative operating conditions and the associated costs for the water systems at the Arizona Public Service Four Corners Station, the Public Service of Colorado Comanche Station, the Georgia Power Co. Plant Bowen, the Pennsylvania Power and Light Montour Station, and the Montana Power Co. Colstrip Plant.

Detailed discussions of the water systems at these plants as well as the recycle/reuse alternatives studied for each are presented in Appendices F through J. It should be noted here that this analysis was performed to study general water recycle/reuse alternatives. Actual implementation of any of these alternatives would require a more extensive investigation of process variability. More water quality data would be required along with additional studies to fully characterize the ash.

5.1 APS Four Corners

The major water consumer other than the cooling pond (Morgan Lake) at Four Corners is the particulate/SO_2 scrubbing system. Cooling is accomplished by recirculating water from Morgan Lake. Bottom ash is sluiced in a recirculating fashion with Morgan Lake providing the sluice water. All of the recycle/reuse alternatives for Four Corners concern themselves exclusively with the scrubbing system since scaling problems have been encountered and an effective water management scheme necessitates scale free operation of the scrubbing system. Since Morgan Lake is already part of two recirculating systems (bottom ash, cooling) no additional recycle/reuse alternatives were investigated. To do so would involve considering the effects on heat dissipation from the pond and is beyond the scope of this project.

Four alternatives were investigated for the particulate scrubbing system at Four Corners. Table 5-1 presents a summary of these four alternatives compared to existing operations.

The results of the first alternative simulation indicates that the present system tankage capacity is not sufficient to allow ample gypsum precipitation to prevent scaling. These results are based on the assumption that 98.6% of the sorbed SO_2 is oxidized to sulfate in the scrubbers. In cases where the oxidation is less than 98.6%, less tankage capacity will be required to prevent scale. Since gypsum precipitation is the controlling factor at these levels of oxidation, lower oxidation rates will lower the amount of gypsum to be precipitated and therefore require a smaller reaction tank. In all four alternatives oxidation was assumed to remain at the level measured at the plant. Studies conducted at Four Corners after this work was completed showed that addition of lime to the venturi recirculation tank lowered the sulfite oxidation to a level where the scrubbers operate in the subsaturated mode with respect to gypsum. The hold tank volume required to prevent scale in this mode is much smaller than the volumes predicted in this study where high oxidation was assumed.

In the second alternative, a tank capacity of 37,500 cubic meters (1.33×10^6 cubic feet) was simulated. Gypsum relative saturations were reduced to levels below the critical level required for the on-set of scaling. Two cases were studied with different scrubber liquid-to-gas ratios (L/G). The existing L/G of 4.7 ℓ/m^3 @STP (35.2 gal/1000 scf) gave a scrubber bottoms pH of 2.9 and an L/G of 10.0 ℓ/m^3 @STP (74.8 gal/1000 scf) gave a pH of 3.9 (assuming 50% SO_2 removal), indicating that higher L/G's are desirable for corrosion control

The third alternative simulation, recycling the ash pond overflow to the scrubbing system, indicated that the pond overflow has no major impact on the gypsum relative saturations in the system but reduces the water makeup requirements from 70.7 ℓ/sec (1122 GPM) for Alternative 2 to about 50.8 ℓ/sec (807 GPM). Also, a simulation with ash pond overflow recycle using a reaction tank volume of 21,200 m^3 (7.5×10^5 ft^3) showed that a more reasonable reaction tank volume can be utilized. This simulation showed a gypsum relative saturation of 1.19 in the scrubber effluent slurry.

TABLE 5-1. SUMMARY OF RECYCLE/REUSE OPTIONS AT FOUR CORNERS[1]

	Existing Condition		Alternative Two		Alternative Three		Alternative Four
	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2	Case 1
Weight Percent Solids in Thickener Bottoms	10	30	30	30	30	30	30
Hold Tank Volume, m^3 (ft^3)	0	0	37,500 (1.33×10^6)	37,500 (1.33×10^6)	37,500 (1.33×10^6)	21,200 (0.75×10^6)	8900 (0.31×10^6)
Liquid to Gas Ratio, ℓ/m^3 @ STP (gal/scf)	4.7 (35.2)	4.7 (35.2)	4.7 (35.2)	10.0 (74.8)	10.0 (74.8)	10.0 (74.8)	10.0 (74.8)
% Recycle from the Ash Pond	0	0	0	0	28	28	0
SO_2 Removal, %	30	30	50	50	50	50	50
Oxidation, %	98.6	98.6	98.6	98.6	98.6	98.6	98.6
Particulate Removal prior to scrubber, %	None	None	None	None	None	None	60
Scrubber Makeup Rate, ℓ/sec (GPM)	223 (3540)	70.7 (1730)	70.7 (1120)	70.7 (1120)	50.8 (805)	50.8 (805)	41.0 (650)
Costs:							
Capital, 1976 $	--	--	3,334,000	4,275,000	4,328,000	3,317,000	3,385,000
Operating, 1976 $ [2] (mils/kWh)	--	--	628,000 (.128)	1,101,000 (.225)	1,109,000 (.226)	958,000 (.195)	968,000 (.198)

[1] Rough cost estimates were made to compare technically feasible options and do not include a "difficulty to retrofit" factor.

[2] Includes capital cost amortization of 15% per year.

The fourth alternative shows that reaction tank volume may be decreased further by removing a portion of the fly ash by dry methods prior to the scrubbing system. A volume of 8900 m^3 (3.14×10^5 ft^3) was used to obtain a gypsum relative saturation of 1.19 in the scrubber effluent (60% of fly ash removed prior to scrubber). Water makeup requirements were also reduced to 41.0 ℓ/sec (650 GPM).

The rough cost estimates of the technically feasible options (Alternatives 2-4) indicate that three to four million dollars would be required to upgrade the particulate scrubbing system so that scale potential is eliminated and water requirements reduced. The least expensive alternative was Alternative 3, case two (recycle ash pond overflow, reduced reaction tank volume), followed closely by the fourth option. Alternative 2, cases one and two, and Alternative 3, case one showed similar installed costs. Energy consumption did not vary radically among alternatives, although Alternative 2, case one (increased tank volume, low L/G) indicated a lower energy requirement was necessary and therefore less operating costs. The operating costs shown in Table 5-1 include capital amortization at 15% per year.

5.2 PSC Comanche

The major water consumers at Comanche are the cooling towers and the bottom ash handling systems. There is no SO_2 scrubbing and the fly ash is presently trucked off site. As part of the study of the water system at Comanche wet fly ash sluicing was also considered.

Table 5-2 presents a summary of the three alternatives which were examined for Comanche. The first one involved using cooling system blowdown from the towers operating at five cycles of concentration to sluice fly ash and bottom ash on a once-through basis. The effects of CO_2 mass transfer in the ash pond and the sluice tank were examined for this system. No gypsum scale potential was identified in any of the once-through sluicing cases, but potential scaling of $CaCO_3$ and $Mg(OH)_2$ was present. Although gypsum relative saturation was less than the critical value (1.3-1.4) variations in ash or makeup water quality may cause gypsum scale. The calculated relative saturation for gypsum was 1.24. This alternative will result in an ash pond overflow of about 32.7 ℓ/sec (518 GPM) for each unit as compared to the existing configuration pond overflow rate of about 78 ℓ/sec (1230 GPM) per unit.

TABLE 5-2. SUMMARY OF WATER RECYCLE/REUSE OPTIONS AT COMANCHE[1]

	Existing Conditions	Alternative One	Alternative Two	Alternative Three
Cooling Tower Makeup Source	Softened River Water	Softened River Water	Softened River Water	Softened River Water
Cycles of Concentration in Cooling Towers	5.0	5.0	7.6	8.4
Cooling System Treatment	(Sulfuric acid and zinc polyphosphate used for all conditions)			
Fly Ash Disposal Method Type, % solids	Dry	Wet, 10%	Wet, 10%	Dry
Bottom Ash Disposal Method Type, % solids	Wet, 1%	Wet, 4% [2]	Wet, 4% [2]	Wet, 1%
Recycle in Fly Ash System, %	---	0	10%	---
Recycle in Bottom Ash System, %	0	0	100%	100%
Treatment in Ash Systems	None	None	Brine Concentration of Makeup (50%)	None
Plant Makeup Requirements ℓ/sec (GPM)	590 (9350)	520 (8250)	455 (7210)	450 (7120)
Plant Discharge ℓ/sec (GPM)	156 (2470)	65.4 (1040)	28.8 (460)	30.2 (480)
Costs				
Capital Investment, 1976 $	---	342,000	3,662,000	222,000
Operating Expenditures, 1976 $/yr [3] (mils/kW-hr)	---	90,000 (0.02)	863,000 (0.18)	38,000 (0.008)
Additional Cost to Treat Pond Overflow for Zero Discharge				
Capital, 1976 $	---	8,280,000	3,706,000	3,883,000
Operating, 1976 $/yr [3]	---	2,136,000	944,000	989,000
(mils/kW-hr)	---	(0.43)	(0.19)	(0.20)
Total Cost for Zero Discharge				
Capital, 1976 $	---	8,622,000	7,368,000	4,105,000
Operating, 1976 $/yr [3]	---	2,226,000	1,807,000	1,027,000
(mils/kW-hr)	---	(0.45)	(0.37)	(0.21)

[1] Rough cost estimates were made to compare technically feasible options and do not include a "difficulty to retrofit" factor.

[2] Sluicing bottom ash at 4% solids may not be feasible due to hydraulic limitations of equipment.

[3] Includes capital cost amortization at 15% per year.

The second alternative involves using cooling system blowdown at 7.6 cycles of concentration as makeup to a recirculating ash sluice system. The makeup water was used to sluice fly ash, and recycled ash pond water was used to sluice bottom ash. Only 10% of the fly ash sluice water was recycled from the pond. Gypsum relative saturations in the fly ash sluice line were calculated to be 1.54 - 1.74 depending on the level of CO_2 transfer in the pond. This range exceeds the critical relative saturation range for scaling of $CaSO_4 \cdot 2H_2O$ of 1.3 - 1.4. Therefore, some form of treatment would be required such as brine concentration of a portion of the tower blowdown. Lime treatment of the blowdown for calcium removal was found to be insufficient for scale prevention due to the sulfate concentrations in the system. Desupersaturation of gypsum in the ash pond will also not prevent scaling since only a small portion of the ash pond liquor is recycled to the fly ash system. This alternative will produce an ash pond overflow of about 14.4 ℓ/sec (230 GPM) for each unit.

The third alternative is to continue to dispose of fly ash in a dry form and sluice the bottom ash on a recirculating basis at 1% solids using cooling tower blowdown and pond recycle with the towers operating at 8.4 cycles of concentration. This will provide 16.0 ℓ/sec (260 GPM) of cooling tower blowdown per unit and will not alter the boiler refractory cooling requirements. For this alternative about 15.1 ℓ/sec (240 GPM) of ash pond overflow per unit is obtained. This water may be discharged or recycled to the boiler and cooling tower makeup systems after appropriate treatment.

Rough cost estimates were make for the once-through sluice system and the recirculating system (Alternatives 1 and 2) using cooling tower blowdown to sluice fly ash with 50% of the blowdown treated by brine concentration. Operating the cooling system at 5 cycles of concentration and sluicing the fly ash and bottom ash on a once-through basis is the less expensive alternative ($342,000 for capital cost and about $90,000/yr operating cost, including capital amortization at 15% per year). The third alternative is the least expensive of the three. Capital costs are about $222,000 and operating costs are about $38,000/yr, including capital amortization at 15% per year.

In order to reduce the ash pond overflow to 14.4 ℓ/sec (229 GPM) for each unit by operating the cooling systems at 7.6 cycles of concentration with the cooling system blowdown as sluicing makeup, the entire plant ash sluice system will require an initial capital cost of about $3.7 million and an operating cost of about $863,000/yr, including capital amortization at 15% per year. These costs do not include the possible necessity of silica removal.

If zero discharge of ash pond overflow is desired, the once-through system becomes more expensive due to the greater amount of ash pond overflow to be treated. A softening/reverse osmosis/brine concentration system to eliminate ash pond overflow would require an additional operating cost of approximately $2,136,000/yr. The total overall costs would be about $8,622,000 for capital costs and $2,226,000/yr for operating costs (including capital cost amortization).

The additional costs for obtaining zero discharge with the recirculating system would be about $3.7 million for capital costs and $944,000/yr for operating costs, giving total overall costs of about $7.4 million for capital costs and $1.8 million/yr for operating costs including capital amortization at 15% per year.

The costs associated with achieving zero discharge with dry fly ash disposal (third alternative) are about $4.1 million for capital costs and $1,027,000/yr for operating costs. Since fly ash is currently disposed of in a dry fashion at Comanche, no additional costs for the fly ash system are needed. This makes the third alternative the least expensive for achieving zero discharge. These costs include brine concentration, additional piping, additional pumping costs, and capital cost amortization at 15% per year.

5.3 GPC Bowen

The major water consumers at Bowen are the cooling towers and the ash handling systems. Bowen does not employ any SO_2 or particulate scrubbing.

Table 5-3 presents a summary of the technically feasible operations and the relative costs of each of these alternatives. Two process alternatives were studied for the ash sluicing system at Bowen. The first case involved using cooling tower blowdown from the towers operating at 5.7 cycles of concentration to sluice both bottom and fly ash on a once-through basis at about 10 wt. % solids (Alternative 1 in Table

TABLE 5-3. SUMMARY OF TECHNICALLY FEASIBLE OPTIONS AT BOWEN[1]

	Existing Condition	Alternative One	Alternative Two	Alternative Three
Cooling Tower Makeup Source	Makeup Pond, Service Water	Makeup Pond, Service Water	Makeup Pond, Service Water	Makeup Pond, Service Water, Brine Concentrator Distillate
Cycles of Concentration in Towers	1.7	5.7	15.	15.
Cooling System Treatment	None	H_2SO_4	H_2SO_4	H_2SO_4
Acid Addition Rate, kg/day[2] (lb/day)	0 (0)	481 (1060)	608 (1340)	608 (1340)
Ash Sluice Makeup Source	Cooling Tower Blowdown	Cooling Tower Blowdown	Cooling Tower Blowdown	Cooling Tower Blowdown
% Recycle in Fly Ash System	0	0	60	60
% Recycle in Bottom Ash System	0	0	100	100
Ash System Treatment	None	None	Recycle Softening	Recycle Softening, Brine Concentration of Pond Overflow
Plant Makeup Requirements, ℓ/sec (GPM)	3250 (51,500)	1880 (29,800)	1670 (26,400)	1630 (25,800)
Plant Discharge Rate, ℓ/sec (GPM)	1600 (25,000)	255 (4050)	41 (650)	0 (0)
Costs				
Capital, 1976 $	--	100,000	1,223,000	6,380,000
Operating, 1976 $/yr[3]	--	52,900	402,000	1,735,000
(mils/kw-hr)		(.002)	(.018)	(.078)

[1] Rough cost estimates were made to compare technically feasible options and do not include a "difficulty to retrofit" factor.

[2] As 100% H_2SO_4.

[3] Includes capital cost amortization at 15% per year.

5-3). The effects of CO_2 mass transfer in the ash pond and sluice tank on the system operation were investigated. No gypsum scale potential was identified in any of the cases with once-through ash sluicing.

The second alternative for the ash sluicing system involved using cooling tower blowdown from the towers operating at 15.0 cycles of concentration as makeup water to a recirculating ash sluice system (Alternative 2 in Table 5-3). A blowdown of 41 ℓ/sec (650 GPM) is taken from the ash pond for this alternative. If the pond recycle water remains supersaturated with respect to gypsum, scaling will occur in this system. However, this situation may be remedied by chemical treatment. Sodium carbonate softening of approximately 80% of the pond recycle water will maintain a gypsum relative saturation of about 1.0 in the slurry line and prevent calcium sulfate scaling. The calcium carbonate sludge produced in the softening step may be disposed of in the ash pond.

Zero discharge from the cooling and ash sluicing systems (Alternative 3 in Table 5-3) may be achieved by installing a softening/reverse osmosis/brine concentration unit to treat the above ash pond overflow (41 ℓ/sec or 650 GPM) and recycling approximately 50% of the clean water as boiler makeup and the remainder as cooling tower makeup.

Potential scaling of $CaSO_3$ is present in all cases studied, both once-through and recirculating. However, the fly ash slurry line possibly can be kept free of plugging by the addition of a fly ash slurry reaction tank and by frequent flushing with a water stream of pH 6-7. Pilot or bench-scale testing is recommended to determine accurately the size of reaction tank and frequency and quantity of acid washing required or if other measures are necessary.

The rough cost estimates presented for the alternatives in Table 5-3 indicate that reducing the ash pond overflow to 225 ℓ/sec (4050 GPM) by running the cooling towers at 5.7 cycles of concentration and sluicing the ash on a once-through basis using cooling tower blowdown is the less expensive option (about $100,000 capital cost with about $53,000/yr operating costs). This option necessitates acid treatment in the towers. The operating expenses include capital amortization at 15% per year.

Reducing the ash pond overflow to about 41 ℓ/sec (650 GPM) by operating the cooling towers at 15.0 cycles of concentration (with acid treatment) and using the tower blowdown as makeup to a recirculating ash sluice system (with Na_2CO_3 softening of 80% of the pond recycle) has an initial capital cost of about $1,223,000 and operating costs including capital cost amortization (15% per year) of about $402,000/yr. The use of a softening/reverse osmosis/brine concentrator unit to eliminate the ash pond overflow discharge (recycle to boiler and cooling tower makeup) for this alternative would require a capital investment of about $6.38 million total. The additional operating costs would be about $1,222,000/yr, giving a total of approximately $1,735,000/yr.

5.4 PP&L Montour

The water system at Montour is similar to the one at Bowen. Once-through wet sluicing of both fly and bottom ash is employed and there is no equipment to handle SO_2. The cooling towers at Bowen and at Montour are natural draft.

Table 5-4 presents a summary of the technically feasible options for the Montour water system as compared to existing operations and the relative costs of each of these alternatives. Four process alternatives were studied for the water systems at Montour. All alternatives sluiced bottom ash and fly ash at 5 wt. % solids. Mill rejects were sluiced at 0.5% solids. In all cases ash pond liquor was recycled to the ash sluicing operation. In one case, Alternative 4, a blowdown was taken from the system to prevent $CaSO_4 \cdot 2H_2O$ scale. The other three alternatives did not discharge any liquid streams and controlled $CaSO_4 \cdot 2H_2O$ scale with softening of a portion of the pond recycle water.

The first alternative assumes that the cooling tower drift from one tower was equal to the design value of 32 ℓ/sec (500 GPM). Enough blowdown was drawn from the cooling towers to serve as makeup to the recirculating sluicing operation. Under this situation the cooling tower should be operating near 8 cycles of concentration.

The second alternative is identical to Alternative 1 except that the cooling tower drift was assumed to be negligible. This assumption increased the cycles of concentration from 8 to 20 even though the blowdown rate was not changed. This had the effect of requiring more softening for the pond recycle stream because of the poorer quality of makeup water to the ash sluicing operations.

TABLE 5-4. SUMMARY OF TECHNICALLY FEASIBLE OPTIONS AT MONTOUR[1]

	Existing Condition	Alternative 1	Alternative 2	Alternative 3	Alternative 4
Cycles of Concentration in Cooling Towers	1.5 - 2.0	8	20	20	20
Assumed Drift Rate in Cooling Towers ℓ/sec (GPM)	62 (1,000)	62 (1,000)	0	40 (650)	40 (650)
Blowdown from Cooling Towers ℓ/sec (GPM)	725 (11,500)	48 (760)	40 (650)	0	0
% Recycle in Fly Ash Sluicing System	0	89.	89.	89.	73.
Sluice System Makeup Source	Cooling Tower Blowdown	Cooling Tower Blowdown	Cooling Tower Blowdown	River Water	River Water
Total Makeup Water Rate, ℓ/sec (GPM)	1,500 (24,000)	1,000 (16,000)	950 (15,000)	985 (15,600)	1,035 (16,400)
Ultimate Effluent Rate, ℓ/sec (GPM)	500 (7,900)	0	0	0	50 (800)
Treatment Required	None	H_2SO_4 (Cooling Tower)[2] Na_2CO_3 (Pond Recycle)[3]	H_2SO_4 (Cooling Tower)[2] Na_2CO_3 (Pond Recycle)[3]	H_2SO_4 (Cooling Tower)[2] Na_2CO_3 (Pond Recycle)[3]	H_2SO_4 (Cooling Tower)[2]
Costs					
Capital, 1976 $	--	640,000	668,000	622,000	485,000
Operating, 1976 $/yr[4]	--	173,000	187,000	169,000	103,000
(mils/kW-hr)		(0.016)	(0.018)	(0.016)	(0.010)

---

[1] Rough cost estimates were made to compare technically feasible options and do not include a "difficulty to retrofit" factor.

[2] Sulfuric acid treatment for $CaCO_3$ scale control.

[3] Na_2CO_3 softening for Ca removal.

[4] Includes capital cost amortization at 15% per year.

Reproduced from best available copy.

The other two alternatives assume that the cooling towers can be operated at zero blowdown. This requires that the drift be at least 65% of the design value. Under these alternatives the makeup water to the ash sluicing operation is obtained directly from the Susquehanna River or the plant makeup pond. Alternative 3 employed softening and attained zero discharge similar to the two previous alternatives. Alternative 4 controlled the $CaSO_4 \cdot 2H_2O$ scaling potential by the use of a blowdown stream of about 50 ℓ/sec (800 GPM) from the ash pond (both units).

Potential scaling of $CaCO_3$ is present in all four cases. However, the fly ash slurry line possibly can be kept free of plugging by the addition of a fly ash slurry reaction tank and/or by flushing with acidic water. Pilot or bench scale testing is recommended to determine accurately the size of reaction tank and frequency and quantity of acid washing required or if other measures are necessary.

Rough cost estimates for the different alternatives are also presented in Table 5-4. Alternative 4 is the least expensive due to the fact that no softening was required. The other three vary mostly in the degree of softening that was required for the recirculating ash sluicing system. It should be emphasized that Alternatives 1 and 2 differ only in the assumption concerning the drift rate in the cooling towers. If more information could be obtained about the actual drift rate, a more reliable cost estimate could be made.

5.5 MPC Colstrip

The major water systems at the 350 Mw/unit Colstrip plant are the cooling tower and combined SO_2/particualte scrubbing systems. Colstrip is designed for and is achieving zero discharge through brine concentration of the cooling tower blowdown and a disposal pond for the scrubber sludge.

Table 5-5 presents a summary of the two combined system alternatives for the Colstrip water system as compared to existing operating and the relative costs of each alternative. All flows reported in Table 5-5 refer to those produced from both units.

The first alternative does not involve any changes in operation of the cooling towers but uses cooling tower blowdown and untreated river water as scrubber makeup as opposed to softened river water and brine concentrator distillate as is presently done. A capital cost of $159,000 is reported for piping

TABLE 5-5. SUMMARY OF WATER RECYCLE/REUSE OPTIONS AT COLSTRIP[1]

	Existing Conditions	Alternative One	Alternative Two
Cooling Tower Makeup Source	Softened River Water	Softened River Water	Untreated River Water
Cycles of Concentration in Cooling Towers	13.5	13.5	20
Cooling System Treatment	Makeup Softening	Makeup Softening	Slip-stream softening
Treatment Rate, ℓ/sec (GPM)	423 (6710)	397 (6300)	18 (284)
Cooling Tower Blowdown Rate, ℓ/sec (GPM)	23.6 (376)	23.6 (376)	14.6 (230)
Scrubber Makeup Source	Softened River Water, Brine Concentrator Distillate	Cooling Tower Blowdown, Untreated River Water	Cooling Tower Blowdown, Untreated River Water
Plant Makeup Rate ℓ/sec (GPM)	423 (6710)	423 (6710)	423 (6710)
Plant Discharge Rate ℓ/sec (GPM)	0.	0.	0.
Costs: [1]			
Capital, 1976 $	--	159,000	275,000
Operating, 1976 $/yr. [2]	--	-237,000	-217,000
(mils/kwh)	--	(-.046)	(-.044)

---

[1] Rough cost estimates were made to compare technically feasible options and do not include a "difficulty to retrofit" factor.

[2] Includes capital cost amortization at 15% per year.

modifications and new pumps. However, a net operating savings is shown due to a large savings in brine concentrator operation because of the reduced flow. Only enough cooling tower blowdown is sent to the brine concentrator to provide the boiler makeup requirements (only one brine concentrator needed).

Alternative 2 includes using slipstream treatment in the cooling tower system in addition to the system changes of Alternative 1. The towers are operated at 20 cycles of concentration resulting in decreased blowdown. Again only enough cooling tower blowdown to provide the boiler makeup is sent to the brine concentrator. A higher capital cost is reported due to the conversion to slipstream treatment in the cooling system. The increased capital charges result in a lower operating expense savings for this alternative. The savings in brine concentrator operating costs represents the major savings of both of these alternatives.

Although the Colstrip plant is achieving zero discharge, more effective cascading of the water streams in the plant may be achieved which results in a decrease in operating costs from the existing level. The capital and operating costs reported in Table 5-5 do not include any savings which could have been realized if the Colstrip water system had been designed for the most effective cascading of aqueous streams. A savings in capital investment could have been achieved by designing the cooling towers for slipstream treatment and by using only one 150 GPM capacity brine concentrator as opposed to the two 200 GPM capacity units presently used. It should be noted that MPC considered sidestream softening but did not implement it since it was not believed to be reliable technology. The capital savings associated with purchasing one 150 GPM brine concentrator versus two 200 GPM units totals about $1.9 million based on $7,750/GPM (LE-239).

5.6 Recycle/Reuse Alternatives in Combined Systems

Minimization of makeup requirements and aqueous discharges from coal-fired steam-electric generating stations requires efficient cascading of the aqueous streams within the whole plant. The best arrangement for any plant is the water use scheme which attains the required environmental standards at the least possible cost. The optimum balance of these conflicting requirements is not always obvious. Therefore, several alternatives were presented for each power plant. Although conditions varied from plant to plant the alternative water systems presented were similar in their overall approach to water utilization.

The cooling towers require the largest amount of water at most plants. They also need water of reasonably high quality to insure that scale will not form in the condenser. The makeup requirements to the cooling towers are usually supplied directly from the water source for the plant, the highest quality large supply of water. The towers concentrate the dissolved solids in this water because of the evaporation that occurs in the tower. A blowdown from the tower is usually required to control the level of dissolved solids and prevent scale formation. The size of the blowdown stream can be reduced if acid treatment and/or softening are used to inhibit scale formation. The size and quality of this blowdown stream makes it a good candidate for makeup to other plant water consumers such as ash sluicing or scrubbing operations.

All of the alternatives studied for the four power plants employing cooling towers have the cooling towers serving as the major recipient of the plant makeup water. Smaller uses of the plant makeup include feed to the demineralizers, for boiler makeup, and general service water. The remaining plant water needs are supplied by the cooling tower blowdown.

Two of the plants studied, Bowen and Montour, employ wet fly and bottom ash sluicing. All of the makeup to these systems is supplied from the cooling towers. The rate of cooling tower blowdown at Montour is determined by the water requirement for the once-through sluicing system. Excess blowdown is discharged at Bowen. In order to meet the once-through ash sluicing water demand, the blowdown from the towers is much larger than necessary to control condenser scale. The rate at which water is delivered to the ash ponds in once-through systems is greater than the rate at which it is lost from the ponds through evaporation and occlusion with the pond sludge. This excess water from once-through sluicing usually is discharged.

Recirculating ash sluicing systems were investigated as a potential recycle/reuse scheme. The systems were designed to use much less cooling tower blowdown by sluicing the ash with a mixture of pond water and cooling tower blowdown. In some of the alternatives studied for Montour, the size of the cooling tower blowdown was equal to the losses that occur in the pond, thereby attaining zero discharge. At the increased cycles of concentration realized because of the reduced cooling tower blowdown, acid treatment was needed to prevent $CaCO_3$ scale in the condensers. Softening of the pond recycle stream was needed to control $CaSO_4 \cdot 2H_2O$ scale in the ash slurry line. At Bowen softening of 80% of the pond recycle stream was required to control gypsum scale in a recirculating ash system with 60% of the fly ash sluice water recycled. To attain zero discharge with this system would require an expensive treatment step, such as brine concentration, for the pond overflow. The quality of the cooling tower blowdown and the reactivity of the fly ash at Comanche was such that a recirculating fly ash sluicing system would probably scale the slurry lines at 10% recycle without softening. Softening of the recycle stream at 10% recycle would not be effective since the recycle represents only a small portion of the total sluice water. It was recommended that Comanche continue to dispose of their fly ash by dry methods.

The design of the Colstrip water system and alternatives suggested in this study are similar to the other proposed systems. The cooling tower makeup is the major portion of the water entering the plant and the blowdown from the towers serves as makeup to other water consumers. Some of the water is lost in the SO_2 scrubbers via evaporation and occlusion with the scrubber sludge and some of the water is lost in the recirculating bottom ash system.

The present operation of the Colstrip plant is at zero discharge. The alternatives proposed for the water system suggest ways to attain zero discharge at reduced cost. The major savings occurs because the alternatives do not use as much brine concentration as is presently used. Only enough water to supply boiler makeup is sent to the brine concentrators.

In summary, the three major water consumers with increased recycle/reuse opportunities at coal-fired power plants are cooling towers, ash sluicing, and SO_2/particulate scrubbing. Cooling ponds may also be considered as major water consumers but the study of thermal dispersion in ponds was beyond the scope of this project. An investigation of increased recycle in cooling ponds would require that the effects on the pond heat dissipation be considered. The cooling towers demand the highest quality water and produce a fairly large blowdown stream. A desirable method to achieve zero discharge is to limit the cooling tower blowdown to a level no greater than the total makeup requirements for the other water consumers. The ash sluicing and SO_2/particulate scrubbing systems serve as good water sinks because of the water losses occurring through evaporation and occlusion with sludges in these systems. Cooling tower blowdown can be used to sluice ash either in a once-through or recirculating system or as makeup water to a scrubbing system (excluding demister wash).

GENERALIZED IMPLEMENTATION PLANS

1.0 INTRODUCTION

Limited availability and rising costs of water along with reduced discharge requirements have placed an ever increasing importance on water recycle/reuse at coal-fired power plants. The first part of this project involved investigating water recycle/reuse alternatives of five typical power plants. This section of the final report presents generalized implementation plans for the types of recycle/reuse possibilities identified in the plant studies.

Three types of major water systems were identified as candidates for increased recycle/reuse options at coal-fired power plants. These are cooling tower, ash sluicing, and SO_2/particulate scrubbing systems. At each of the four plants studied with cooling towers, increased recycle was possible in the cooling tower system through the treatment options of sulfuric acid addition for pH control and/or softening for control of gypsum scale potential. For each of the two plants studied with once-through wet fly ash sluicing, a closed-loop recirculating system may be used with softening to control gypsum scale potential. For scrubbing systems, the recycle/reuse options identified include: 1) using a normally discharged stream such as cooling tower blowdown as scrubber makeup in a cascaded water system, and 2) converting from open-loop to closed-loop operation.

The generalized implementation plans for each of these types of recycle/reuse options may be divided into four phases:

Phase I - System Characterization

Phase II - Alternative Evaluation

Phase III - Pilot-scale Studies

Phase IV - Full-scale Operation

The first phase, system characterization, is necessary to establish a data base for determining existing operating characteristics and identifying the types of recycle/reuse options possible. This includes collecting all available design and operating information and a sampling program to supplement existing data. The data base resulting from this phase of the implementation plan can be used to evaluate recycle/reuse options for both extreme and average operating conditions in the second phase. The most important operating variables and their effects on system operation are presented in the characterization phase descriptions.

The plant studies performed in this project used a computer model to evaluate recycle/reuse opportunities. The results of the plant studies showed that computer models are effective in identifying water recycle/reuse options in cooling tower, ash sluicing, and SO_2/particulate scrubbing systems. The second phase of an implementation plan involves an analysis of alternatives to evaluate the feasibility of those alternatives under various operating conditions. Computer simulation results can be used to design necessary treatment step to prevent scale formation, and provide a basis for designing any pilot-scale equipment required for testing particular options. The evaluation discussions in this document include evaluation criteria and a methodology for using a computer model to perform the evaluations.

Pilot-scale studies are listed as the third phase of a generalized implementation plant. These studies may be required to determine parameters which may not be easily measured or calculated from the characterization or simulation phases. For ash sluicing systems, these parameters include: 1) ash reactivity, 2) the effectiveness of including an ash reaction tank prior to the sluice line to reduce scale potential, and 3) the amount of CO_2 transfer occurring in the pond. For scrubbing operations, pilot-scale studies may be required to determine the operability of a revised demister wash operation. Pilot studies are not required for cooling towers since they exist as recirculating systems and may be changed gradually. Care should be taken when implementing a cooling tower system modification. A sampling program to monitor cooling tower operation will minimize the risk of scaling during implementation.

The final phase of an implementation plan is to make full-scale modifications. The pilot-scale test results may be used to design the full-scale modifications. In the case of cooling towers, the full-scale modifications may be based on the results of the evaluation phase of the implementation plan. The following sections discuss each of the phases of an implementation plan as they apply to cooling tower, ash sluicing, and SO_2/ particulate scrubbing systems.

2.0 COOLING TOWERS

Wet cooling towers are generally the largest water consumers at coal-fired electric power plants. The towers disperse the waste heat from the condensers by contacting a recirculating water stream with the atmosphere. Water losses occur from the tower in three ways: evaporation, drift, and blowdown. The sum of these three streams is equal to the makeup requirements for the tower. Evaporation accounts for the majority of the heat lost from the tower. Drift occurs because fine droplets of water are carried off as a mist due to the intimate contact of the air and water. Most cooling towers have mist eliminators designed to minimize drift. The blowdown is a purge stream which is used to control the level of dissolved solids which will build up in the recirculating water. Figure 2-1 shows the general flow scheme for a cooling tower system including the tower and condenser.

The evaporation and drift rates are set by the design of the tower, the ambient conditions, and the cooling load. The blowdown rate is maintained at a level sufficient to prevent scale formation in the condenser. However, as shown by the plant studies portion of this project, in many cooling towers the size of the blowdown is much larger than required to prevent scale formation. Three of the four cooling tower systems investigated could operate at increased recycle through the use of acid addition to control pH. By better defining the limits of scale formation in recirculating cooling systems, the blowdown can be reduced and thus the net water consumption and discharge from these systems can be reduced.

This section presents a methodology for defining the limits of safe cooling tower operation and implementing a demonstration plan. This plan will allow increased recycle and decreased makeup and blowdown requirements. Only three of the four implementation phases discussed in the introduction apply to cooling towers. These are:

Phase I - Characterize Cooling Tower Operation

Phase II - Evaluate Alternatives

Phase III - Design and Implement Full-scale Modifications

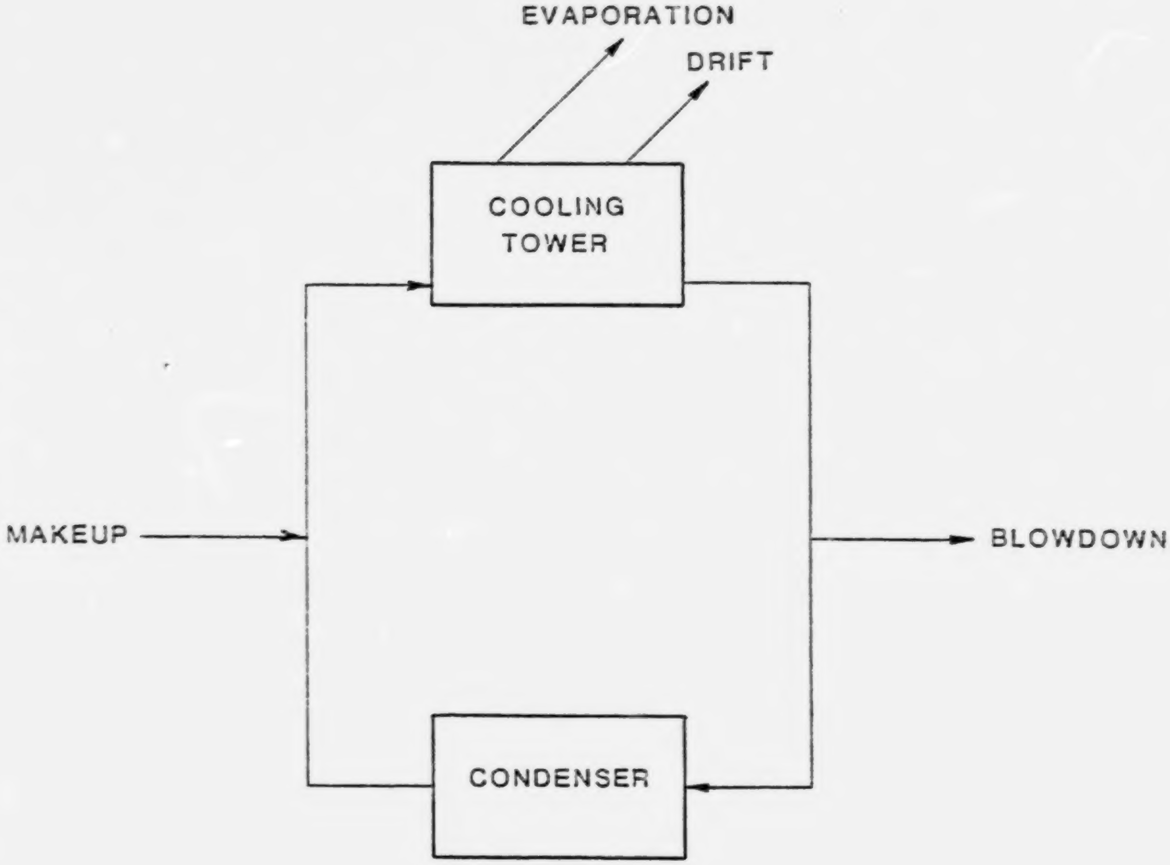

EVAPORATION
DRIFT
COOLING TOWER
MAKEUP
BLOWDOWN
CONDENSER

Figure 2-1. General cooling tower system flow scheme.

The first phase involves collecting the data base which is required to identify reasonable system modifications. The second phase identifies the degree of recycle that can be attained and the amount of treatment that will be required. A detailed design of the modified cooling tower system can be made along with a detailed procedure for implementation of the modifications from the results of the process calculations performed in the second phase. These calculations will allow specification of stream flows, temperatures, compositions, and treatment equipment sizes. Operation of a pilot system is not required for cooling towers because cooling towers already exist as recirculating systems which can be changed in a gradual manner. The cost of building a pilot system would not be justified even though there is a possibility that if the towers are operated incorrectly the main condenser could scale. Care should be taken to safely modify the operation of full scale cooling towers. A comprehensive sampling program will allow the cooling tower operation to be monitored so that the risk of scaling is minimized.

The plant studies conducted in this program involved the first two phases of an implementation plan. Design and operating data concerning four cooling tower systems was collected and used to evaluate operation both under existing and alternative conditions. However, only limited operating data was available concerning these systems.

Implementing the alternatives studied at the existing plants could require some additional studies to better define the variations in operating parameters. These studies would involve a sampling program to define tower operation and evaluation of the system under extreme conditions. The plant studies performed were based on results from one set of grab samples, existing makeup water quality data, and design information for tower operating conditions (air flow, circulating water flow, climatological data, etc.).

The following discussions are written to apply to any cooling tower facility. All phases of an implementation plan are presented although the characterization and evaluation phases have been addressed in the plant studies. Since virtually all cooling tower systems are unique with respect to operating conditions, a detailed characterization and evaluation phase should be conducted before implementing increased recycle at a particular plant site. The purpose of the plant studies was to identify and evaluate the types of recycle/reuse alternatives achievable at coal-fired power plants. The purpose of this document is to outline a procedure for implementing the types of alternatives identified in the plant studies.

2.1 Phase I: Cooling Tower Characterization

In the characterization phase the basic data which describes cooling tower operation is assembled. These data should include information about both average and extreme tower operating conditions. This section discusses the important data for characterizing tower operation. First, the necessary data is discussed and then a sampling plan to supplement available data is presented. If sufficient data is available, a sampling program may not be required before implementing an increased recycle/reuse option.

2.1.1 Identification of Process Variables

Table 2-1 represents a data collection sheet which may be used to assemble cooling tower system operating conditions. This table includes data blanks for acid treatment, softening, and other chemical treatments for cooling tower operations. If the treatment methods are not used, the data concerning them will not be relevant.

The most important stream to obtain long range data about is the makeup water. The makeup water quality determines the quality of all of the other streams in the cooling system. Small changes in the concentrations of dissolved solids in the makeup water are magnified in the blowdown because of the concentrating effect of the cooling tower. Any long range variations in the cooling water quality can be traced to changes in the makeup water. Seasonal variations in makeup water quality may require variations in treatment levels required to prevent scale formation in the condenser. In order to insure that the tower modifications do not cause scaling, the variations in makeup water should be identified.

The calcium, magnesium, sodium, chloride, sulfate, nitrate, carbonate, silica, and TDS concentrations as well as pH are the most important in defining the makeup water quality. Calcium carbonate, calcium sulfate, and silica are the primary scale forming species in cooling towers. The magnesium, sodium, nitrate, and chloride concentrations are important since they affect scale formation through chemical complexing or effects on activity. High chloride concentrations may cause corrosion problems. Phosphate scales may also form if the phosphate level is high. The results of the plant studies indicated that phosphate levels in natural bodies of water are not high enough to cause any scaling problems. Phosphate levels should be checked to insure that the makeup water does not have an unusually high level. If high

TABLE 2-1. GENERAL DATA SHEET FOR COOLING TOWERS

I. Tower Parameters
- A. Drift Rate _____ GPM
- B. Approach _____ °F
- C. Cycles of Concentration _____
- D. Circulating Water Temperature Change _____ °F

II. Ambient Air
- A. Dry Bulb Temperature _____ °F
- B. Wet Bulb Temperature _____ °F
- C. Flow Through Tower _____ ACFM

III. Cooling System Makeup Water
- A. Flow _____ GPM
- B. Composition
  - pH _____
  - total calcium as Ca^{++} _____ mg/ℓ
  - total magnesium as Mg^{++} _____ mg/ℓ
  - total sodium as Na^{+} _____ mg/ℓ
  - total chloride as Cl^{-} _____ mg/ℓ
  - total nitrate as NO_3^{-} _____ mg/ℓ
  - total carbonate as $CO_3^{=}$ _____ mg/ℓ
  - total sulfur as $SO_4^{=}$ _____ mg/ℓ
  - total silica as SiO_2 _____ mg/ℓ
  - total dissolved solids _____ mg/ℓ

IV. Cooling System Blowdown
- A. Flow _____ GPM
- B. Composition
  - pH _____
  - total calcium as Ca^{++} _____ mg/ℓ
  - total magnesium as Mg^{++} _____ mg/ℓ

TABLE 2-1. GENERAL DATA SHEET FOR COOLING TOWERS (Continued)

total sodium as Na^+ ______ mg/ℓ
total chloride as Cl^- ______ mg/ℓ
total nitrate as NO_3^- ______ mg/ℓ
total carbonate as $CO_3^=$ ______ mg/ℓ
total sulfur as $SO_4^=$ ______ mg/ℓ
total silica as SiO_2 ______ mg/ℓ
total dissolved solids ______ mg/ℓ

V. Condenser
A. Flow Rate of Cooling Water ______ GPM
B. Temperature of Exit Water ______ °F
C. Condensing Steam Temperature ______ °F

VI. Acid Addition (H_2SO_4)
A. Flow ______ lb/day
B. Wt. % H_2SO_4 ______ %

VII. Softening
A. Additive Type (Lime, Soda Ash, CO_2) ______
B. Amount of Chemical Addition ______ lb/hr
C. Capacity of Treatment Equipment ______ GPM
D. Size of Treated Stream ______ GPM
E. Size of Waste Stream ______ GPM
F. % Solids in Waste Stream ______ %

VIII. Chemical Treatment (Scaling, Corrosion Inhibitors)
A. Type ______
B. Amount ______

levels (>0.1 mg/ℓ) are detected, analysis for phosphate should be included with the other analyses.

Variations in both the individual species concentrations and the total level of dissolved solids can be expected. The full range of possibilities should be identified. This will insure that the treatments which are used in the cooling tower operation will be designed for all of the water qualities which the tower will be expected to operate with.

For characterizing cooling tower operation it is important that climatological data be collected. The wet bulb and dry bulb temperatures are the most important climatological data that must be obtained for cooling tower systems. These data are the determining factors affecting the air flow rate required to meet the heat dissipation demand on the tower.

The wet and dry bulb temperatures affect the evaporative capacity of the air flowing through the tower. Variations in these temperatures will cause variations in the evaporation rate and therefore will affect the makeup requirements of the system. Increased evaporation rates will cause a higher concentration of dissolved solids in the circulating water if blowdown and drift are constant. Equation 2.1 shows the relationship between evaporation, drift, and blowdown rates and the level of concentration occurring in the tower.

$$C = \frac{B + D + E}{B + D} \qquad (2.1)$$

where

C = cycles of concentration

B = blowdown rate

D = drift rate

E = evaporation rate

From this equation it can be seen that changes in the evaporation rate will directly affect the cycles of concentration if the blowdown is held constant.

Expected variations in load placed on the cooling towers should also be identified. Changes in the load should directly affect the evaporation rate in the tower because most of the cooling which occurs is due to evaporation (∼90%). The steam condensing temperature is an important parameter in characterizing a cooling tower system. The highest temperature in the system is in the condenser. This is the most likely point of $CaCO_3$ or $CaSO_4$ scale formation since these species are less soluble at higher temperatures. The condenser temperature should therefore be used when evaluating tower scaling potential.

The data collection discussed so far is concerned with data representing a reasonably long period of time. This data is very useful to characterize the operating conditions of the tower under a variety of natural and man-made variations. Of necessity, this data must be collected over long periods of time and some of it may not be available. To supplement this data, direct sampling of the cooling tower's major streams may be necessary.

2.1.2 Sampling Program

In cases where tower operating data is incomplete, a sampling program should be conducted at the plant for about two weeks. During this period it is recommended that about 3-5 sets of grab samples per day be taken. All of the samples should be taken at approximately the same time to produce a series of "snap shots" of the system operation which can be used to identify deviations from steady-state.

The data which are required include much of the information listed in Table 2-1. The most important samples are of the cooling tower makeup and blowdown. If flow data is available, it should be noted, but the costs of magnetic, turbine, or orifice metering devices for large streams are too expensive to use for a short sampling period. The wet bulb and dry bulb temperatures and the inlet and outlet condenser temperatures should be recorded at the time that the sampling takes place.

The grab samples of cooling tower makeup and blowdown which are taken should be analyzed using the procedures which are reported in the EPA's "Manual of Methods for Chemical Analysis of Water and Wastes". Important parameters include pH, temperature, total dissolved solids, calcium, magnesium, sodium, carbonate, sulfate, nitrate, chloride, and silica.

If any treatment is used, such as acid for scale control or chlorine for biological control, it should be monitored continuously. It is more important that average values of these very small addition streams are known than the instantaneous rate at the time when the grab sample is taken.

If softening is used for the cooling tower, separate grab samples of the inlet and outlet streams from the softeners will be required. Sample analyses of the inlet and outlet stream of the softener are required in the same manner that the cooling tower makeup and blowdown are. The outlet stream from the softener should also be analyzed for suspended solids to determine if the flow rate is too large for the clarifier and sedimentation system. If a substantial level of suspended solids is noticed, then the softener is being overloaded.

Some of the data which is useful to characterize a cooling tower cannot be easily measured. In this case design information or values calculated using indirect measurements must be used. In general, the water recirculating rate, the air flow rate, and the drift are not well known, especially in natural draft towers. Estimates of the water flow rate can be made using data about the inlet and outlet condenser temperatures and the electric load on the generator to estimate the waste heat load. The air flow rate can be estimated using data concerning the load, the ambient conditions and the approach on the tower. The drift is not easily estimated and can only be measured approximately.

To characterize the operation of a cooling tower all sources of information should be consulted. The main sources are historical data kept by the power plant and government agencies, and sampled data which can be obtained over a short period of time. Any of the required data that cannot be found in these two sources can be supplemented by design information and indirect calculations.

2.2 Phase II: Evaluation of Operating Alternatives

The second phase of a cooling tower implementation plan is to formulate and evaluate various modes of cooling tower operation. Formulation of alternative operating conditions will depend on how the cooling tower fits into the overall plant recycle/reuse scheme. The plant studies conducted in this program showed that cooling tower blowdown can be cascaded to other power plant water systems such as ash sluicing and SO_2/particulate scrubbing.

In a plant designed for minimum liquid discharge, the cooling tower blowdown rate is set by the water requirements of the systems which use cooling tower blowdown as makeup. Since evaporation and drift are determined by tower design, the blowdown sets the cycles of concentration required in the tower (see Equation 2.1). The types of water systems used at a particular plant site and therefore the quantity of water required by these systems determine the cycles of concentration required in the cooling tower.

To determine the feasibility of operating the cooling tower system at the cycles of concentration required by a particular recycle/reuse option, both potential scale formation and the level of treatment required should be investigated. The plant studies portion of this project showed that a computer process simulation package is a very useful tool with which to study cooling tower systems. The simulations can be used to identify the operating characteristics of the tower under increased recycle conditions. The results of simulations can also be used to identify the treatment methods required to operate with increased recycle and the degree of treatment necessary. The following sections describe the types of calculations required to evaluate cooling tower operation and a methodology for using a computer model to perform the evaluations.

2.2.1 Evaluation Criteria

The cooling tower evaluation should involve mass and energy balances to calculate the flows, compositions, and temperatures of all of the process streams. The calculations should include predictions of the inorganic aqueous equilibria phenomena that occurs in cooling towers, including solid-liquid and gas-liquid equilibria. The solid-liquid equilibria include all of the important scale forming species: $CaCO_3$, $Mg(OH)_2$, $CaSO_4 \cdot 2H_2O$, SiO_2, and other silicate scales. The gas-liquid equilibria predicitions are necessary to calculate the evaporation rate and the degree of CO_2 transfer that occurs in the tower. These calculations allow cooling tower operation to be evaluated from both the standpoints of scale potential and treatment requirements.

2.2.1.1 Scale Potential

The most important factor which determines what cycles of concentration can be reached in a cooling system is the potential for scale formation in the condenser. If scale does form in the condenser, the heat transfer can be reduced significantly. This will raise the steam condensing temperature, increase the back pressure in the turbine and reduce the efficiency of the power generating cycle.

In the plant studies portion of this study the concept of relative saturation was used to measure the scaling potential of aqueous solutions. For calcium carbonate, a common scale, the relative saturation is defined in Equation 2.2.

$$R.S._{(CaCO_3)} = \frac{(a_{Ca^{++}})(a_{CO_3^{=}})}{K_{(CaCO_3)}} \qquad (2.2)$$

$$= \frac{(M_{Ca^{++}}\gamma_{Ca^{++}})(M_{CO_3^{=}}\gamma_{CO_3^{=}})}{K_{(CaCO_3)}} \qquad (2.3)$$

where

$R.S._{(CaCO_3)}$ = relative saturation of calcium carbonate

$K_{(CaCO_3)}$ = solubility product of calcium carbonate

$a_{Ca^{++}}$ = activity of the calcium ion

$M_{Ca^{++}}$ = moality of the calcium ion

$\gamma_{Ca^{++}}$ = activity coefficient of the calcium ion

$a_{CO_3^{=}}$ = activity of the carbonate ion

$M_{CO_3^{=}}$ = molality of the carbonate ion

$\gamma_{CO_3^{=}}$ = activity coefficient of the carbonate ion

The activities must be used instead of the molalities of the ions in solutions to take into account the non-idealities which exist in aqueous solutions. Equation 2.3 defines relative saturation in terms of ion molalities and activity coefficients. The activity coefficients account for deviations from ideal behavior. In the plant studies portion of this project, these deviations were shown to become larger as the total dissolved solids of the solution increased.

When the relative saturation of a species is below 1.0, no potential for scale formation exists. When it is greater than 1.0, a potential for solids formation exists but scale will not necessarily form. When the relative saturation of a species is above its "critical value", nucleation will occur and scale formation is more likely. The critical value for $CaSO_4 \cdot 2H_2O$ is 1.3-1.4 and in this study, the critical values of $CaCO_3$ and $Mg(OH)_2$ were found to be about 2.5 and 3.4, respectively.

The most common scale forming species in cooling towers is calcium carbonate. The relative saturation of $CaCO_3$ is dependent on the concentration of the calcium and carbonate ions, as shown in Equation 2.3. The calcium concentration depends on the cycles of concentration. The carbonate concentration depends on the pH and the liquid-gas equilibrium between gaseous carbon dioxide and dissolved carbonate. It is necessary that the CO_2 transfer which occurs between the air and the water in the tower is accounted for to accurately predict the relative saturation of $CaCO_3$. This calculation is especially important in cases where there is no pH control because the pH of the circulating water is affected by the amount of total carbonate species in solution.

Figure 2-2 is a sample plot of the relative saturation of $CaCO_3$ in the cooling tower blowdown as a function of the cycles of concentration. This data was obtained using the computer model of cooling towers described in the plant studies portion of the project. This plot shows that the relative saturation of $CaCO_3$ increases in a non-linear fashion, and the curve becomes steeper as the cycles increase. The relative saturation increases at a faster rate at higher cycles of concentration because the pH rises dramatically as a function of cycles, as can be seen in Figure 2-3. The increased pH causes less CO_2 to be desorbed in the towers as well as causing a shift of bicarbonate ions to carbonate ions. The plots shown in Figures 2-2 and 2-3 apply to cooling tower systems where the blowdown is adjusted to keep the cycles of concentration at a low level to prevent scale formation. However, the discussions concerning relative saturation and CO_2 transfer also apply to systems where treatment is used.

2.2.1.2 Treatment Alternatives

In many cases blowdown alone is not sufficient to control $CaCO_3$ scale and pH control may be instituted. Sulfuric

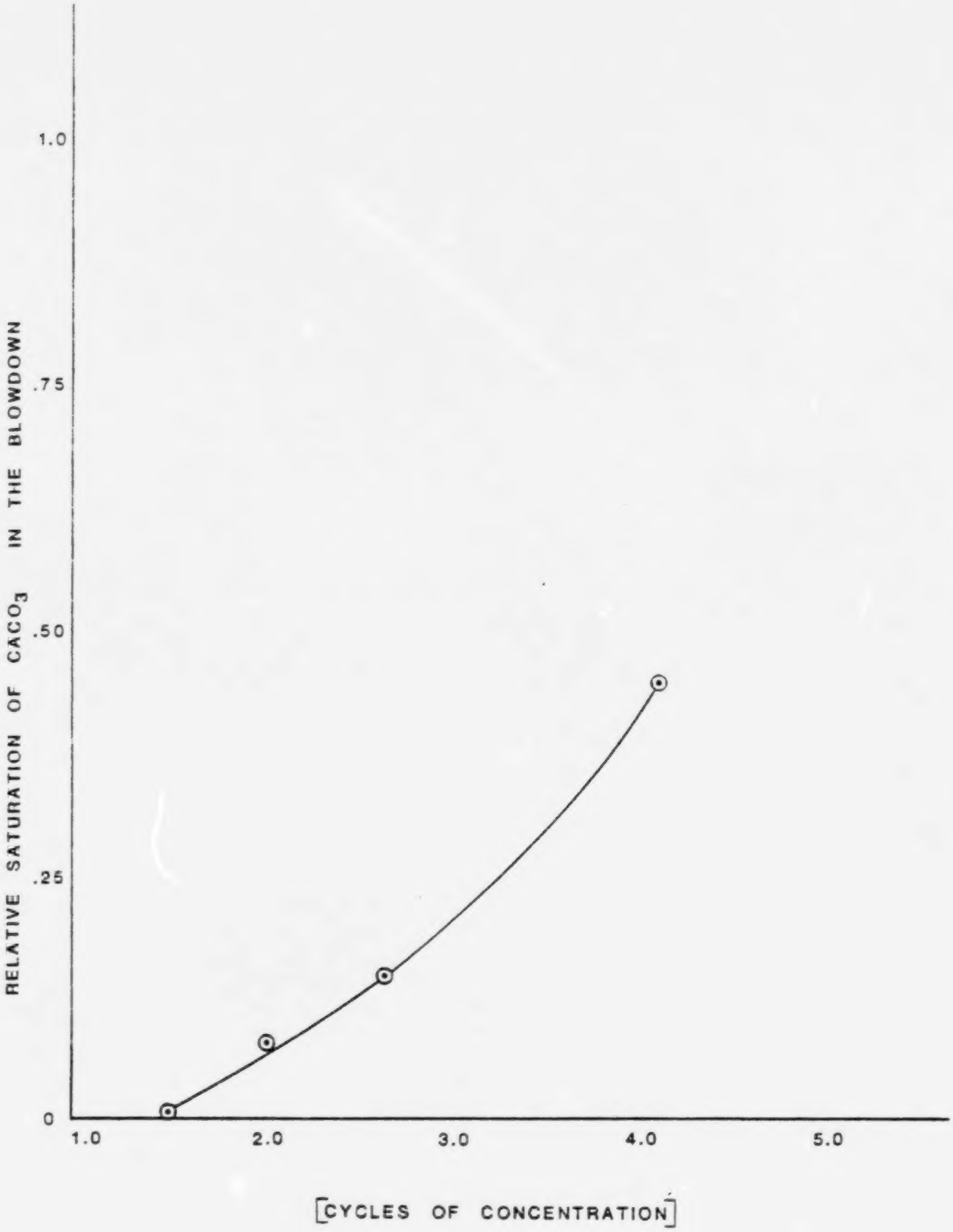


Figure 2-2. $CaCO_3$ scale potential as a function of cycles of concentration in cooling towers without treatment (example).

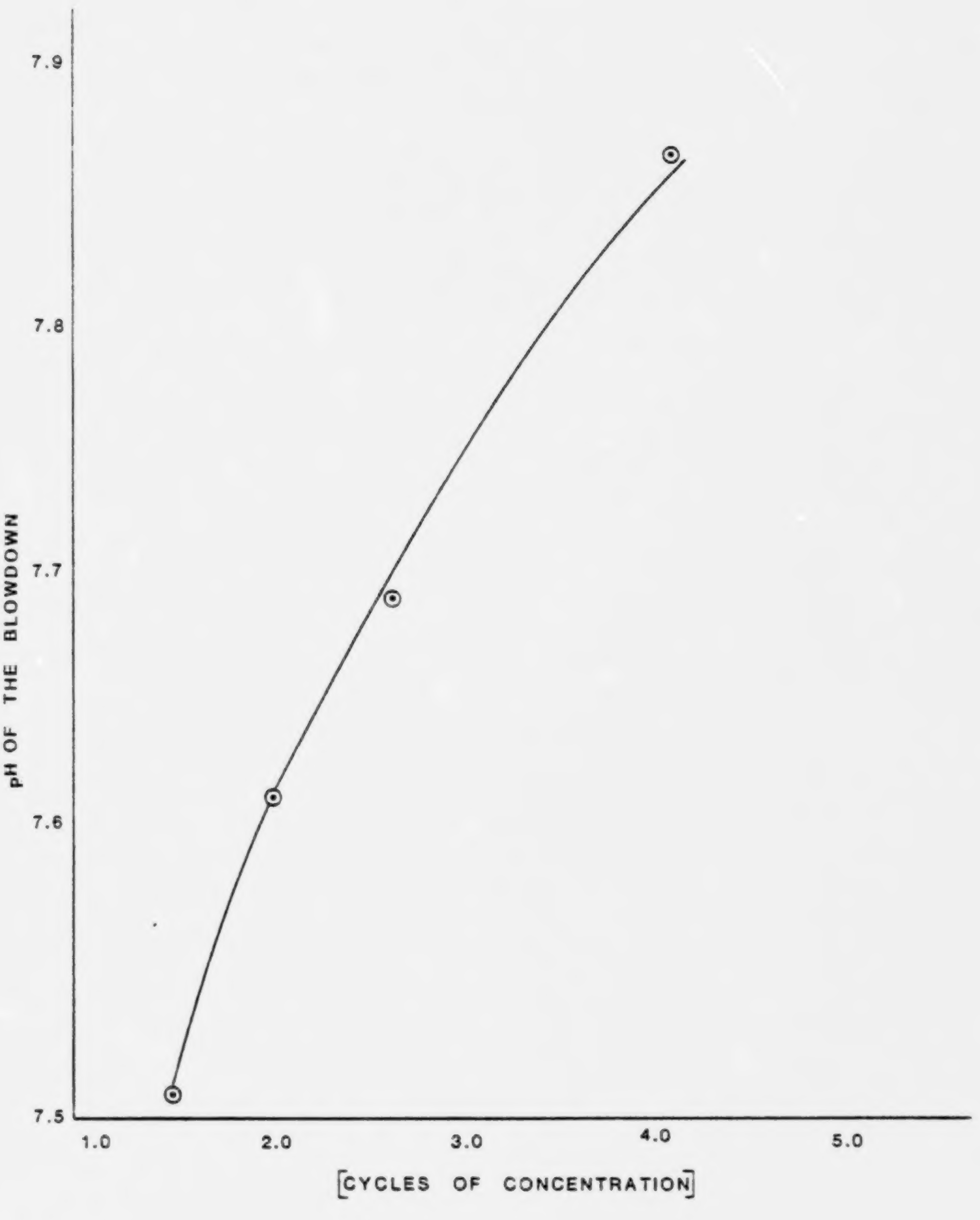


Figure 2-3. Cooling tower blowdown pH as a function of cycles of concentration in towers without treatment (example).

acid treatment is used to control the pH of the recirculating water because it is the least expensive of most commercially available acids. The gas-liquid-solid equilibria calculations identify the pH required to control the relative saturation of $CaCO_3$ to a specified level as well as the amount of sulfuric acid needed to maintain this pH. $Mg(OH)_2$ and some silicate scales can also be controlled with acid addition, but $CaCO_3$ is usually the limiting scale.

$CaSO_4 \cdot 2H_2O$ is another scale that can be encountered in cooling systems. Since its solid-liquid equilibrium is not pH dependent, acid addition will not reduce its relative saturation. The addition of sulfuric acid increases the sulfate ion concentration and actually increases the relative saturation of $CaSO_4 \cdot 2H_2O$, although in most cases this effect is insignificant. When problems are encountered with gypsum scale, softening is required to reduce the calcium concentration, either by pretreatment of the makeup water or slipstream treatment of the recirculating water. The evaluation of a particular option should involve determining the chemical requirements for pretreatment and/or slipstream treatment.

The size of the stream required to be softened must be calculated. This is especially important because it determines the size of the softening equipment which will be required. It is imperative that the softening equipment be able to handle the largest stream that might be necessary to soften. If the equipment capacity is exceeded, the flocculation and sedimentation times are reduced and $CaCO_3$ solids may carry over into the cooling water. The results of this carryover could be a heavily scaled condenser. The maximum stream size should be as small as reasonable though, because the capital cost of the softening equipment is relatively high and is a direct function of the size of the softened stream.

2.2.2 Model Application

A fundamental computer model such as the one used in the plant studies is a very useful tool in performing the calculations discussed above concerning evaluation of cooling tower operation. The cooling tower model should initially be verified for the specific cooling system being studied using the data collected in the characterization phase. This can best be done by inputting data collected during the sample periods and comparing the simulated results to measured values. If the data base is extensive enough, the model assumptions can be altered to improve its reliability. In cooling tower systems parameters such as the air flow rate and the degree of CO_2 transfer are not always known to a high degree of accuracy. These parameters may be adjusted based on extensive operating data to more effectively model the actual tower operation.

The verified model can then be used to simulate alternative operating conditions. The simulations should be performed for the full variety of conditions which the tower can be expected to operate under. The analysis of the available historical data is very useful in the identification of seasonal as well as non-seasonal extremes in weather and water quality. It is very important that the worst case operation is simulated, so that the cooling tower modifications, based upon these simulations, will be able to handle all expected conditions.

The model should not only be used to simulate cooling tower operations which account for long range variations in operating conditions, but also for short-term upsets. The effects of drastic changes in load, steam condensing temperature, drift, blowdown, and climate should be identified with simulations. These simulations identify the kind of changes in treatment rates that the modified system should be able to handle. It is very important that upsets in system operation do not cause the relative saturation of any scale forming species to rise above its critical value, and scale the condenser.

Several simulations should be performed to verify and "fine tune" the model. Alternative operating conditions may require 10-15 simulations of varying ambient and operating conditions. Three to five additional simulations should be performed to estimate the effects of short-term upsets.

The results of these simulations identify the operating conditions which can be expected with increased recycle. They specify the temperatures, flows and compositions of the important streams under various operating conditions. These results establish a sound basis upon which to design an acid treatment system, if necessary, which can operate effectively under all foreseeable situations. If softening is required, the simulation results identify the maximum flow through the softener and the maximum chemical addition rate as well as the quality of the outlet stream from the softener. The results of these simulations should establish a sound basis upon which to design system modifications which will increase the cycles of concentration in the cooling tower but will not reduce the reliability of the system.

2.3 Phase III: Cooling Tower Modifications

After the optimum system operation is identified from the results of the evaluations, a complete design with the new operating conditions can be prepared. This design should include specifications of the flows, temperatures, and compositions of the main process streams as well as all of the new equipment and instruments necessary to monitor the cooling system.

A plan for the necessary changes in operating conditions from the initial system to the modified system can be developed with the new design. The plan will help insure safe operation and minimize disruption to the main operating objectives of the plant, the production of electricity.

This section discusses the kinds of modifications that can be made on a cooling tower to increase the cycles of concentration, and presents examples of how the operating changes could be implemented.

2.3.1 Equipment

In most cooling systems additional equipment will be required to significantly increase the cycles of concentration. This new equipment can include piping, pumps, controllers, feeders, a clarifier, or a thickener. This subsection discusses the equipment necessary to increase recycle in cooling towers.

Additional piping and pumping capacity may be needed to reroute the plant makeup to replace the water which is not supplied by cooling tower blowdown because of the increased recycle in the towers. This will be a temporary situation required only during implementation of the modifications when the cooling tower blowdown is being reduced. If pH control is added to the system, a pump, a storage tank, and a pH controller will be required. The maximum capacity of the metering pump should be larger than the flow rate calculated in the evaluations of worst case conditions. If slipstream or makeup softening is added to the system, a chemical feeder with variable feed rates, a flocculator, and a sedimentation tank will be necessary. The residence time in the flocculator should be at least 40-60 minutes. Sedimentation requires a 2-4 hour residence time. A slurry pump and piping will also be required to pump the softener sludge to the ash pond. The cost of equipment for modifying cooling tower operation will be a strong function of the size of the system and the levels of treatment necessary.

Any new treatments added to the system require additional monitoring. The acid addition can be checked with pH probes to insure that complete mixing of the acid and cooling water occurs. If only partial mixing occurs before the cooling water enters the condenser, corrosion and scale problems might occur. The inlet and outlet streams from the softener should be monitored continuously for conductivity, pH, and turbidity. If a significant increase in turbidity is noticed, the flow rate may be too large for the flocculator and carryover is occurring, also increasing the danger of $CaCO_3$ scale. A common procedure for softening operations is to perform "jar tests" to determine what new operating conditions are necessary for safe operation. However, if increased turbidity is seen, the blowdown from the tower should be increased to avoid any scale formation.

If slipstream treatment is used, the flow through the softener is an important operating variable. The total amount of calcium and magnesium removed in the softening step is directly dependent on the flow and concentration of the calcium and magnesium ions. To effectively control the total amount of hardness removed by the slipstream softener a flow meter should be installed to monitor the flow on a continuous basis.

2.3.2 Implementation

Implementation of cooling tower modifications which involve increased recycle should be performed in a stepwise manner to insure safe operation. Each step should take about a week of monitoring, to insure that the tower is operating as expected. Samples should be taken of the makeup and the blowdown at least twice a day and analyzed for calcium, magnesium, sodium, sulfate, chloride, and carbonate. The TDS can be measured and correlated to conductivity measurements which will give a continuous readout on the quality of the makeup and blowdown streams. Changes in the conductivity of these streams implies that changes in the water quality have occurred and the towers are not operating as expected.

The manner in which increased recycle is implemented can be best illustrated with examples. There are four basic modes of cooling tower operation:

1) Operation at low cycles of concentration so that no treatment is required.

2) Operation at higher cycles of concentration with sulfuric acid addition.

3) Operation at higher cycles of concentration with sulfuric acid addition and softening of the makeup water.

4) Operation at higher cycles of concentration with sulfuric acid addition and softening of a slipstream from the recirculating water.

In the plant studies, two plants which operate their cooling towers in the first mode were identified. These plants operate their natural draft towers at less than three cycles of concentration. These plants have a very high quality makeup to their towers as do most plants which operate without treating their cooling water for scale prevention. Preliminary studies of these cooling tower operations indicate that by changing to the second mode of operation, the towers can operate safely at cycles of concentration as high as fifteen.

To add the capability of pH control to a cooling system only requires a pump, a storage tank, and a pH controller. After this additional equipment is installed, the implementation procedure can be initiated. This implementation procedure should take about five to ten weeks to complete the change from operation at low cycles of concentration to a higher level.

Each step which increases the cycles of concentration by reducing the blowdown should be operated for at least a week. During this period, the pH, temperature, and conductivity of the makeup and blowdown will be monitored continuously. The plant operator should be instructed as to what the maximum acceptable levels in these readings are and to increase the blowdown if anyone exceeds the maximum. It is recommended that complete chemical analyses of the makeup and blowdown streams be performed at least twice a day. The results of these analyses can be used to revise the maximum acceptable levels of the continuous read variables, if necessary. The maximum temperature, pH, and conductivity pertain to a condition very close to the maximum acceptable scale potential.

The relative saturation of $CaSO_4 \cdot 2H_2O$ cannot be controlled by acid addition because it is not pH sensitive. If a cooling tower is operating near the critical scaling value of $CaSO_4 \cdot 2H_2O$, softening is required to increase the degree of recycle. Softening can be used to reduce the calcium level in the makeup or a slipstream from the recirculating water. These levels of operation represent the third and fourth modes listed above.

If softening is being added to an existing system, testing operation of the softener is recommended before the softened stream is fed into the cooling tower system. Complete chemical analyses of the effluent will insure that sufficient calcium is being removed. The pH should be low enough so that $CaCO_3$ or another pH sensitive solid will not form where the makeup is added to the cooling water. The tubidity of the effluent can be measured to insure that complete sedimentation is occurring in the thickener. Jar tests performed on the influent will determine the optimum lime addition rate. Jar testing involves adding various dosage rates to samples of the softener influent. The optimum dosage rate is the lowest rate which still produces a precipitate that settles readily.

After safe operation of the softening equipment is assured, operation of the cooling tower with softening can be attempted. The tower can initially be run at the normal level of recycle with the softening equipment in operation. Complete monitoring of the temperature, pH and conductivity of the makeup, blowdown, and softener effluent is required to track the system operation. The plant operator should be instructed as to the maximum acceptable levels of each of these variables. Complete analyses of these streams at least twice a day are recommended. Daily jar tests are necessary to determine the optimum level of lime addition. Operation at each step should be carried out at least a week before the level of recycle is increased further.

Softening the makeup stream will control $CaSO_4 \cdot 2H_2O$ scale and is easier to control that slipstream treatment, since the softener is not in the cooling loop itself. The results of Phase I of this study have shown that slipstream treatment is more efficient and can allow a greater degree of recycle in cooling towers with smaller capital costs for equipment. If a plant wishes to change its cooling system from pretreatment to side-stream treatment, this could be accomplished by repiping the system.

In the case of existing softening equipment, reliability has been proven for softening the makeup stream. Therefore, initial tests of the repiped system will be short. The system should be monitored continuously, as discussed earlier for softening in general, and the recycle should be increased in a stepwise manner. Because the quality of the slipstream tends to fluctuate more than the makeup water, more frequent jar tests are recommended. As with the other system modifications complete change from initial operation to final operation should take about five to ten weeks.

In summary, there are four basic modes of cooling tower operation. As the treatment level becomes more complex from acid addition to slipstream softening, the degree of recycle achievable also increases. To change modes and increase the cycles of concentration in the cooling tower will usually require about five to ten weeks after all new equipment is installed. This time is required to insure safe operation of the cooling towers at all times and to educate the operating personnel.

3.0 ASH SLUICING

The ash sluicing system is a major water consumer at many coal-fired power plants. Most plants sluice the bottom ash on an intermittent basis from the boiler to a pond where the ash settles. Fly ash is usually removed from the flue gas by an electrostatic precipitator, a mechanical collector, or a fabric filter. The fly ash collected by these means is often sluiced from the collection mechanism to an ash pond for final disposal. The bottom ash and fly ash can be sluiced to a common pond or separate ponds.

Bottom ash is usually sluiced in a slurry of 1-5% solids and fly ash is sluiced at 5-10% solids. Losses occur via evaporation from the surface of the pond, occlusion with the ash in the bottom of the pond (~50% solids), and seepage through the pond liner. The remaining sluice water must then be discharged or used somewhere else in the plant.

Because ash pond overflow is usually high in dissolved solids it is not suitable for many other uses in the plant. One possible consumer of ash pond overflow is a scrubbing system. However, the makeup requirements for a scrubbing system are usually much smaller than the ash pond overflow from a once-through sluicing operation. Therefore, possible recycle/reuse alternatives involving ash sluicing operations necessarily include the possibility of closed-loop or partially closed-loop systems. The plant studies portion of this project investigated both closed-loop ash sluicing and partially closed-loop operations. In a closed-loop system, all of the ash pond overflow is recirculated to sluice ash. The only water losses from this type of system are occlusion with the ash in the pond and evaporation. In a partially closed-loop system, a portion of the ash pond overflow is recycled and the remainder is either cascaded to a water consumer such as a scrubbing system, or it is discharged.

Figure 3-1 shows a general recirculating ash sluicing system. Some recirculating bottom ash sluicing systems presently operate without significant problems. Two of the plants studied in this project operate recirculating bottom ash sluicing systems without scale formation in the slurry lines. Bottom ash is essentially non-reactive and does not serve as a major source of dissolved solids to the slurry liquor. Fly ash is generally much more reactive and a significant amount of dissolved species can be leached from the ash when it is slurried with water. Most fly ash sluicing systems are once-through operations, with the pond overflow discharged.

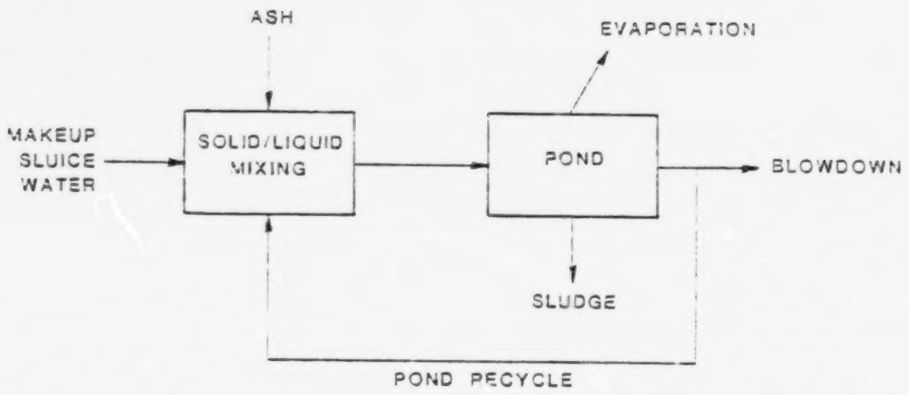


Figure 3-1. Recirculating ash sluicing flow scheme.

This section presents a methodology for implementing a recirculating ash sluicing system. This is broken into four phases:

Phase I - System Characterization

Phase II - Alternative Evaluation

Phase III - Pilot-scale Studies

Phase IV - Full-scale Operation

The first phase involves collecting a data base which is required to identify reasonable system modifications. The second phase identifies the degree of recycle attainable without treatment to prevent scale formation. If a greater level of recirculation is required, the second phase also identifies the treatment requirements to achieve that level.

The evaluation of alternatives in Phase II will depend heavily on the accuracy of the ash reactivity data collected in Phase I. The results of the plant studies portion of this program showed that ash reactivity is a strong function of both the pH and dissolved solids content of the sluice water. The transfer of CO_2 between the atmosphere and the ash pond will affect the pond pH and therefore affect the ash reactivity. The relationship between ash reactivity and sluice water composition is a very complex one and deserves pilot studies to better evaluate recirculating ash sluice systems. The third phase in the implementation plan is to conduct pilot studies to better define the ash reactivity in a recirculating system and to evaluate treatment options for preventing scale formation.

The final phase of the implementation plan for recirculating ash sluicing is to design and startup the full-scale system.

3.1 Phase I: Ash System Characterization

In the characterization phase, the basic data necessary to evaluate a recirculating ash sluicing system is assembled. These data include information about both average and extreme operating conditions. This section discusses the important data for characterizing an ash sluicing operation. First, the important process variables are presented and discussed. Next, a sampling plan to supplement existing data is presented. Finally, bench-scale studies to further characterize the particular ash to be sluiced are outlined.

3.1.1 Identification of Process Variables

The major process variables which affect the feasibility of implementing a recirculating ash sluicing system are listed below:

1) Reactivity of the ash,

2) Rate of production of ash,

3) Surface area of the ash pond(s),

4) Local climatological data,

5) Sluice water flow and composition,

6) Degree of CO_2 transfer between the pond liquor and the atmosphere.

The most important parameter is the ash reactivity. The ash reactivity is defined as the amount of soluble species in the ash. The results of the plant studies portion of this program showed that the major species leached from the fly ashes studied are calcium, magnesium, sulfate, and sodium. When the ash is contacted with water, these species dissolve and may cause calcium carbonate or calcium sulfate scale formation.

The collection of accurate data concerning ash reactivity is therefore extremely important when evaluating the feasibility of a recirculating ash sluice system. The plant studies conducted earlier in this program showed that the ash reactivity varies considerably from plant to plant and that the reactivity of a particular ash is a function of the sluice water composition. The best way to collect accurate ash reactivity data is through sampling and experimental studies. These methodologies are presented in the following sections.

The rates that fly and bottom ash are produced determine the amount of water required as makeup to a sluice system. In a recirculating system, the total makeup required is the sum of the water lost through occlusion with the ash in the pond and through evaporation. The rate of ash production and the percent solids the ash will settle to determine the amount of water lost through occlusion.

The pond surface area and local climatological conditions determine the rate of water lost from the pond through evaporation. The makeup rate required is therefore partially determined by the pond area and climate.

As previously stated, the sluice water flow and composition affects the ash reactivity. The makeup water will, to some extent, determine the type and levels of dissolved salts present in the recirculating system.

The last parameter listed, CO_2 transfer, will affect the pH and carbonate concentration of the pond recycle liquor, and thereby affect the ash reactivity. Characterizing the amount of CO_2 transfer occurring is a very difficult task. Not only does the CO_2 transfer depend on the pond pH but it also depends on the amount of surface agitation resulting from wind. The plant studies portion of this project investigated the two extremes of CO_2 transfer: no transfer and complete equilibrium with the atmosphere. The actual level will be between these two extremes. Pilot studies to evaluate recirculating ash sluice systems may provide data which can be used to better predict the level of CO_2 transfer in full-scale systems.

3.1.2 Sampling

Sampling of an existing operation is one method to determine ash reactivity. By sampling the sluice water and the ash slurry entering the pond, the amount of soluble species in the ash may be calculated. However, this calculation is dependent on the assumption that no precipitation occurs in the sluice line. To determine if a potential for precipitation exists, analyses of the ash slurry liquor can be used to predict scale potential. A sampling program can also provide information concerning variations in ash reactivity. A one to two week sampling program should provide sufficient data to evaluate an existing ash sluice system with respect to ash reactivity.

Three to five samples from each slurry being sluiced to the pond(s) should be taken each day. It is recommended that the inlet and outlet streams be sampled simultaneously, if possible, to obtain a series of "snapshots" of the system operation. These samples can be analyzed using procedures outlined in the EPA's "Manual of Methods for Chemical Analysis of Water and Wastes" for pH, temperature, total dissolved solids, total suspended solids, calcium, magnesium, sodium, carbonate, sulfate, nitrate, chloride, and silica.

If flow data is available, it should be noted, but the costs of magnetic, turbine, or orifice metering devices for large streams are too expensive to install for a short sampling period. Ash flow rates data can be combined with the analysis for suspended solids in the slurries to calculate the fly ash and bottom ash slurry flow rates.

Samples of the ash which are produced during this sampling period should be obtained and labeled. These samples can then be studied under laboratory conditions and the results can be compared to the results measured under actual operating conditions. This comparison can improve the usefulness of the laboratory findings.

3.1.3 Laboratory Studies

In many systems the ash may serve as the largest source of dissolved species in the sluice water. This is especially true when a recirculating fly ash system is operated where the pond water is continually brought in contact with fresh ash and only a small amount of "cleaner" makeup water. Depending on the level of ash reactivity, dissolved species concentrations may increase to the point where $CaCO_3$, $CaSO_4$, $Mg(OH)_2$, or other scales form in the sluice line and restrict the flow of the slurry. A well designed system will not operate for any significant period of time in the scaling mode. In order to design a recirculating ash sluicing system that will not scale under normal operating conditions it is important to predict the reactivity of the ash.

Samples of both the bottom and fly ash which are produced at the plant should be obtained if recirculating systems for both are being considered. In most cases the reactivity of the fly ash is much higher than the bottom ash. Samples of both should be studied initially because the reactivity of ash is affected by many parameters. The reactivity of ash is known to be a function of the mine it is from, the furnace it is burned in, and the conditions at the time of combustion. Therefore, it is important that multiple samples of the ash from all of the coals burned at the plant are obtained so that a reasonable range of the ashes produced at the plant are studied. The reactivity of a given ash sample is also a function of the pH and composition of the sluice water. This requires multiple tests to obtain a reasonable estimate of how the reactivity will change with leachate composition.

Two types of laboratory studies were used to determine ash reactivity in the plant studies portion of this program. Beaker leaching studies with deionized water were performed at various pH's to determine the maximum level of soluble species in the ash. Recirculating bench-scale studies were also conducted. The results of these two types of experiments indicated that the amount of species dissolving from ash is much smaller in a recirculating system than the level determined from the beaker leaching studies. The bench-scale results should more closely reproduce actual conditions and therefore should be used to characterize ash reactivity.

A flow schematic of the bench-scale apparatus used in the plant studies is shown in Figure 3-2. This equipment may be operated with varying degrees of recycle by adjusting the blowdown rate. A mixing tank was used to contact the ash with pond recycle and makeup water. The ash slurry then flows from the tank to the settling pond where the ash settles. The pond recycle and makeup water were transported with peristaltic pumps and the ash was added via a worm screw feeder.

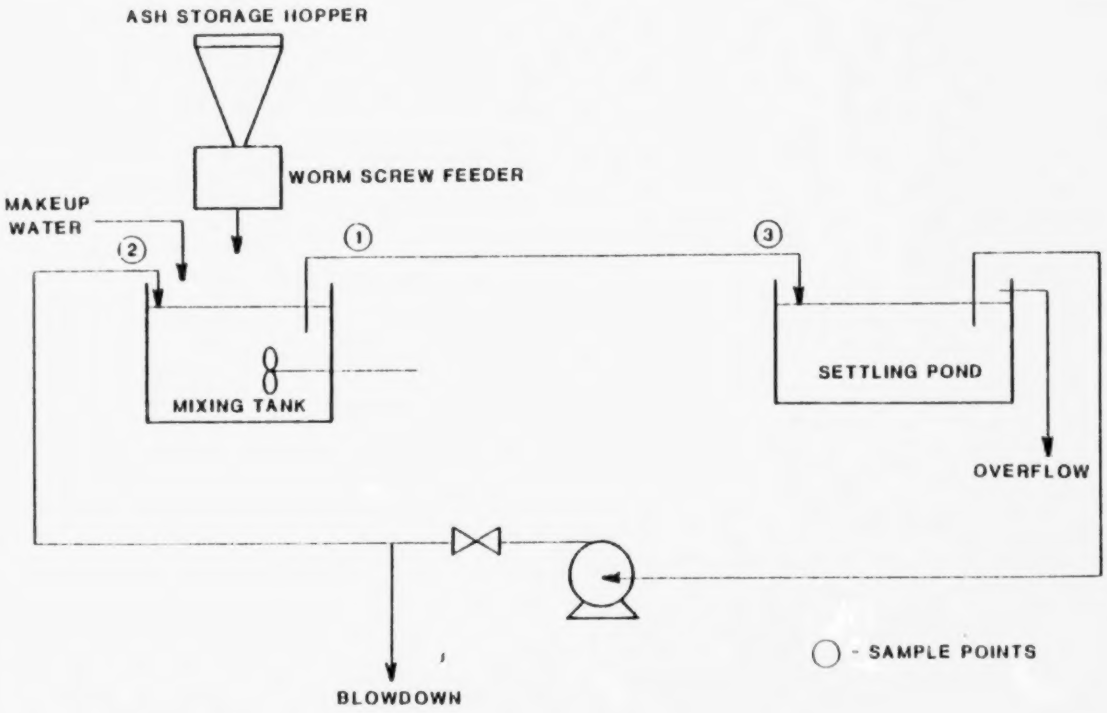

ASH STORAGE HOPPER
WORM SCREW FEEDER
MAKEUP WATER
②
①
③
MIXING TANK
SETTLING POND
OVERFLOW
BLOWDOWN
○ - SAMPLE POINTS

Figure 3-2. Bench-scale model of ash sluicing facilities.

By sampling the makeup water, pond recycle water, and the ash slurry, and monitoring the flows of ash, makeup water, blowdown, and pond recycle, material balances around the mixing tank may be made to determine ash reactivity. Analyses of the aqueous samples taken should include calcium, magnesium, sodium, chloride, carbonate, sulfate, nitrate, and silica. Variations in mixing tank residence time, blowdown rate, recycle rate, and makeup water quality may be used to evaluate ash reactivity and potential scaling problems under different operating conditions.

In order to facilitate the completion of bench-scale experiments within a reasonable time period, the size of the equipment should be considered. With the equipment used in the plant studies, about 30 hours were required for the system to reach steady-state. The pond liquor residence time was about 6 hours. Therefore, about five residence times were required for steady-state operation. The equipment must be sized before ash samples are obtained so that an adequate amount of ash may be available for the system to reach steady-state.

The number of experiments required for a particular ash will depend on the levels of variations in operating parameters identified as being likely and the chosen equipment size.

3.2 Phase II: Evaluation of Operating Alternatives

The second phase of a recirculating ash sluicing implementation plan is to formulate and evaluate various modes of operation. Formulation of alternatives will depend on how the ash sluice system fits into the overall plant recycle/reuse scheme.

If the ash sluicing operation is the final water consumer in a minimum discharge cascaded plant water system, then all of the pond overflow must be recycled. This mode represents completely closed-loop operation. If some of the pond overflow is required as makeup to another water consumer such as a scrubbing system, then only a portion of the pond overflow is recycled. This mode represents a partially closed-loop operation.

To determine the feasibility of operating a closed-loop or partially closed-loop ash sluicing system, both potential scale formation and the level of treatment required should be investigated. The plant studies portion of this project showed that a computer process simulation package is a useful tool to study ash sluicing operations. A computer model can be used to evaluate scale potential and treatment alternatives based on the characterizing data collected in the first phase. It should be noted here that the evaluation of alternatives will depend heavily on the ash reactivity data collected and the amount of CO_2 transfer which is assumed. The following sections describe the types of calculations required to evaluate recirculating ash sluicing systems and a methodology for using a computer model to perform the evaluations.

3.2.1 Evaluation Criteria

The recirculating ash sluice system evaluation should include mass and energy balances to calculate the flows, compositions, and temperatures of all of the process streams. The evaluations should involve predictions of solid-liquid and gas-liquid equilibria for the species occurring in the system. Important solid-liquid equilibria include $CaCO_3$, $Mg(OH)_2$, $CaSO_4 \cdot 2H_2O$, SiO_2, and other silicate scales. Gas-liquid equilibria prediction is necessary to account for CO_2 transfer between the ash pond and the atmosphere.

Any examination of a recirculating ash sluice system will require that certain assumptions are made. Steady-state operation must be assumed so that an answer can be obtained with a reasonable level of computational effort. Dissolution and precipitation may be assumed to be instantaneous or calculated rates which are consistent with measured data can be used. The evaluation should include predictions of system operation under varying conditions of CO_2 transfer between the pond and the atmosphere. Plant measurements taken in Phase I of this project showed that some CO_2 transfer occurs but complete gas-liquid equilibrium between the ash pond and the atmosphere is not achieved. The evaluation must assume a reasonable percent solids in the settled sludge in order to predict the loss of water from the system due to occlusion with the solids.

No real system operates under steady-state conditions for a significant period of time, but a steady-state evaluation under worst case conditions is very usefull for design of a system which can operate safely under all conditions. Instantaneous dissolution and precipitation is a worst case assumption and may cause overdesign. Therefore, rate data should be used when available although this is not very easily obtained for many species. Depending on the reactivity of the ash and the composition of the pond liquor, CO_2 transfer can increase or reduce the scaling potential of the slurry in the sluice line. The sludge that normally settles in ash ponds is in the range of 40% to 60% solids although it is not normally homogeneous. The calculations and assumptions outlined above allow a proposed recirculating ash sluicing system to be evaluated with respect to scale potential and treatment requirements.

3.2.1.1 Scale Potential

The most important factor which determines the feasibility of implementing a recirculating ash sluicing system is the potential for scale formation in the ash slurry pipeline. If significant scale deposits are formed in the pipeline, plugging and subsequent interruption of the production of power may occur.

In the plant studies portion of this study, the concept of relative saturation was used to predict scaling potential. When the relative saturation of a species is below 1.0, no potential for scale formation exists. When it is greater than 1.0, a potential for solids formation exists but scale will not necessarily form. When the relative saturation of a species is above a "critical value", nucleation and scale formation is likely. The critical value for $CaSO_4 \cdot 2H_2O$ is 1.3-1.4. In the plant studies portion of this project the critical values of $CaCO_3$ and $Mg(OH)_2$ were experimentally determined to be about 2.5 and 3.4, respectively. A detailed definition of relative saturation was given in Section 2.2.1.1

Although the critical value of $CaCO_3$ was experimentally determined to be about 2.5, samples taken of existing once-through ash sluicing operations showed $CaCO_3$ relative saturations as high as 38.8 without scaling problems. This may be due to erosion by the ash slurry or the ash particles may be providing precipitation sites for $CaCO_3$. It should be emphasized here that if the evaluation of an alternative predicts a $CaCO_3$ relative saturation greater than 2.5, a potential for scale formation exists but operational problems resulting from heavy scale deposits may not occur. Pilot studies to better define $CaCO_3$ scaling problems in recirculating ash sluice systems are recommended before full-scale operations are implemented.

3.2.1.2 Treatment Alternatives

In an ash sluicing system where excess scaling potential is identified, treatment may be required to reduce the scaling potential. The ash sluicing evaluation should consider treatment technologies and the effects of these technologies on the system operation. Potential treatment technologies for ash sluicing systems include:

1) A reaction tank with sufficient residence time to allow the major portion of the reactive part of the ash to dissolve and to allow for controlled precipitation of any supersaturated species that might otherwise scale in the slurry line.

2) Softening to reduce the levels of calcium and magnesium in the water being recirculated to the sluicing operation.

3) Treatment to reduce the level of dissolved solids in the water being recirculated for sluicing the ash (brine concentration, reverse osmosis, etc.).

The first treatment that should be investigated is the installation of a reaction tank at the point where the ash and the water are contacted. A reaction tank in the system will allow a large portion of the soluble ions in the ash to dissolve leaving the remaining ash essentially inert. The tank also allows any supersaturated species to precipitate in a controlled fashion similar to the way $CaSO_4 \cdot 2H_2O$ and $CaSO_3 \cdot \frac{1}{2}H_2O$ precipitate in a reaction tank in lime/limestone SO_2 scrubbing systems. The results of bench-scale ash studies may indicate the rate of leaching from the ash. Precipitation rates of solids can be obtained from the literature or laboratory studies. The residence time of the reaction tank should be large enough to allow sufficient ash dissolution and solids precipitation to prevent scale formation in the sluice lines. Pilot operations are recommended for sizing a full-scale reaction tank.

Other possible treatments that will reduce scaling potential in the slurry are softening, brine concentration, reverse osmosis, etc. These treatments can best be employed on the water which is recirculated from the ash pond. Softening, the less expensive of the two options, can reduce the calcium and magnesium levels in the recirculating water. Other treatments can be used to remove all types of dissolved solids from a portion of the recirculating water, or from the pond overflow.

In many cases softening can be used to effectively reduce the level of calcium and magnesium to levels where the addition of the reactive species from the ash will not produce a scaling situation in the slurry line. Calculations should be performed to determine what level of softening may be required. In some cases treating only a slipstream from the recirculating water may be necessary to reach the level of calcium and magnesium that will not cause scaling. The size of this slipstream is a very important parameter which determines the size of softening equipment that should be specified for pilot or full-scale implementation. Softening should be more expensive to build and operate than a reaction tank but significantly less expensive than other more elaborate treatments.

Brine concentration can be used as a treatment option for recirculating ash sluicing systems. A discharge from the pond can be treated and the clean water sent to the boiler demineralizer and/or some other plant water consumer. The major effect on the ash sluicing system from this treatment option is that more makeup water is required to operate the system. Since the makeup water is lower in dissolved solids than the pond water, the scale potential in the slurry line is reduced.

3.2.2 Model Application

A computer model such as the one used in the plant studies is a very useful tool in performing the evaluation of a recirculating ash sluice system. However, since ash dissolution kinetics are not well understood at this time, the results of the computer calculations are based on instantaneous dissolution. The evaluations of ash sluicing systems are therefore heavily dependent on the ash reactivity data input. A computer model can be used to perform multiple calculations which demonstrate the effects of variations in the input data. The two factors which are the most difficult to quantify accurately are ash reactivity and CO_2 transfer in the pond. For each alternative evaluated, multiple simulations should be performed to determine the effects of variations in both ash reactivity and the amount of CO_2 transfer.

Bottom ash is usually much less reactive than fly ash. For this reason, most recirculating bottom ash systems will not be prone to scale formation. If the bottom ash system is going to be operated completely independent of the fly ash system, a few simulations will usually be sufficient to show that the bottom ash can be sluiced in a recirculating system without scale. If the bottom ash is unusually reactive, more extensive study of recirculating systems may be required, in which case steps similar to those proposed for recirculating fly ash systems would be appropriate.

The key stream in an ash sluicing system is the slurry which is transported to the ash pond. If scaling problems are encountered, they most likely will occur in the slurry where a significant increase in total dissolved solids is usually experienced because of the dissolution of the reactive portion of the ash. When simulating ash sluicing systems, it is useful to assume that all of the reactive solids identified in the leaching studies enter the liquid phase instantaneously. This assumption allows the worst possible scaling potential to be identified. If the relative saturations of all of the potential scaling solids are less than the critical values, this indicates that the system can be safely operated under the simulated conditions.

If scaling is indicated, treatment of the slurry or recirculating water may be required. The results of computer simulations may be used to size the necessary treatment equipment for scale prevention. However, pilot studies are recommended to better define treatment requirements before full-scale implementation.

3.3 Phase III: Ash Sluicing Pilot Studies

For ash sluicing systems with essentially unreactive ash, pilot studies may not be justified. For recirculating systems sluicing only bottom ash, the results of evaluations may indicate that the scale potential of the slurry is small, in most cases. These recirculating systems can be designed for full scale operation as only a pond return line and additional pumps will be required.

For ash sluicing systems where scaling in the slurry line is a concern because of a combination of reactive ash and poor water quality, pilot studies would be very important, and could produce significant savings in the full-scale design. The pilot system should include the treatment options identified in the optimum system which resulted from the evaluations. The pilot system should be designed at a reduced scale which is dimensionally consistent with the expected full-scale design.

Figure 3-3 is a diagram of a general pilot-scale facility. The system employs a reaction tank, a softener, and a blowdown capability necessary to implement the three major forms of treatment discussed previously. The clarifier serves the same purpose as the ash pond in a full-scale system. The clarifier separates the slurry into a sludge and a solids-free liquid stream which can be recirculated via the return line to slurry additional

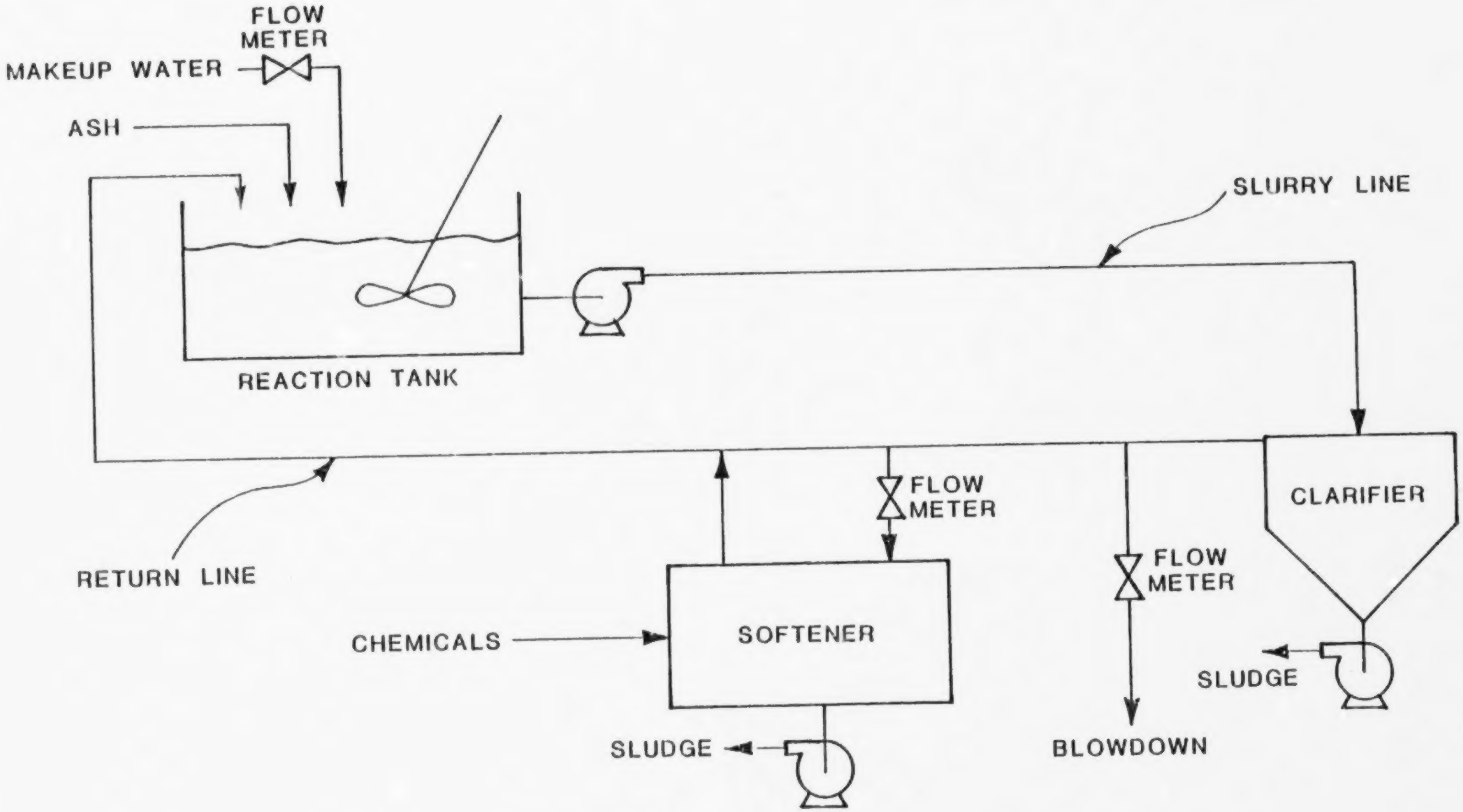

FLOW
METER
MAKEUP WATER
ASH
SLURRY LINE
REACTION TANK
RETURN LINE
FLOW
METER
FLOW
METER
CLARIFIER
CHEMICALS
SOFTENER
SLUDGE
SLUDGE
BLOWDOWN

Figure 3-3. General pilot scale ash sluicing facility.

ash. A clarifier has a much smaller residence time than an ash pond, and thus allows the total system to attain steady-state in a reasonably short time. This allows a larger number of experiments to be performed with the clarifier as opposed to a system with a large settling pond. If a clarifier cannot achieve the solids concentration expected in a pond, a vacuum filter may be added to the system.

A pilot system such as this can best be used on-site at a power plant. The plant can serve as a source of ash and the ash pond can be used as a receptacle for the sludge from the clarifier and the softener. The system should be built near the ash pond where there generally is enough space for such a facility. This will allow for short lines from the facility to the pond and should keep the generally crowded area near the plant itself free. If this kind of location is chosen a dry method must be used to transport the ash from the source, near the plant, to the pilot facility.

Once the pilot facility is constructed on-site, a series of experiments should be performed with the ash from the plant under various operating conditions. Each experiment should be performed for a long enough period to attain steady-state operation. The amount of time required will vary with the design and flow rates chosen. Important variables which should be studied include the makeup water quality, the residence time in the reaction tank, the degree of recycle, the weight percent solids in the slurry, and the size of the softened stream. Data may also be taken to better define CO_2 transfer in the system.

The makeup water should be similar to the water that is expected to be used in full-scale operation. If a number of makeup water sources are being considered, experiments with the full range of makeup water qualities should be performed. In general, the water used for these experiments should have a TDS level and pH near the levels expected in the makeup water for full-scale operation.

The residence time in the reaction tank is a very important parameter to study in the pilot studies. The residence time of a reaction tank can be changed by varying the level of the slurry in the tank, and, thereby, the effective volume, or by varying the flow through the tank. Thus, with one piece of equipment, a wide range of residence times can be studied. The tank must be large enough to attain the maximum desired residence time at the minimum flow rate that will still produce turbulent flow in the slurry line. All smaller residence times can be attained by increasing the flow rate or reducing the level in the reaction tank.

For a given ash flow rate the makeup water requirement is determined by the water lost from the system via evaporation, occlusion with solids in the pond, and blowdown from the system. The sum of the makeup water and the recycled water is determined by the weight percent solids desired in the slurry. Experiments should be performed which vary the percent solids in the slurry and the blowdown from the system. These both directly affect the percent recycle that exists in the system, and, therefore, the quality of the water entering the reaction tank. The weight percent solids in an ash sluicing system can usually vary from 0.5% to 5% solids for bottom ash and 1% to 15% solids for fly ash. The degree of recycle can be varied from zero, in a once-through system, to greater than 80% for systems that operate with minimum discharge.

The softening equipment should be designed to operate on a slipstream from the recycle line. This is the most efficient location for this operation because the highest concentration of calcium and magnesium will exist in this stream. For the pilot design the softener should be large enough to handle all of the largest recycle streams that the system can be expected to operate with. In this way the level of softening can be varied from 0 to 100% of the recycle stream for all conditions studied.

Preliminary experiments should be performed under conditions similar to those simulated with the computer model. Samples of the ash slurry, clarifier underflow, clarifier overflow, softener effluent and makeup water should be taken periodically until steady-state is achieved. Analyses of these samples for suspended solids, calcium, magnesium, sodium, chloride, nitrate, carbonate, sulfate, silica, pH, and TDS will allow the system to be evaluated with respect to scale potential. Material balances may be performed around the reaction tank to calculate ash reactivity. These analyses will also allow evaluation of the softening equipment performance. These preliminary results can be compared to the simulated results and used to design further experiments under conditions closer to optimum operation. These preliminary experiments should only be performed long enough to attain steady-state operation and obtain samples of the key streams.

Experiments under conditions that have been identified as desirable from the preliminary experiments should be performed for longer periods of time to insure that scaling will not be a problem. These experiments can be used to identify optimum operating conditions. They will identify the minimum reaction tank volume, the minimum softening requirement and the maximum percent recycle that can be attained with the ash and makeup water used at the plant. The total task should take about six months to perform with 3-6 people working on the system. Costs associated with the pilot studies will depend on the number of experiments to be performed as identified from the evaluation phase and preliminary sluicing operations.

The results of these studies will establish a strong base upon which to design a full-scale system that will operate with scale problems, minimize the discharge from the ash sluicing system and be as economical as possible to build and operate. The next subsection is devoted to a discussion of full-scale implementation of a recirculating ash sluicing system at an existing facility.

3.4 Phase IV: Full-scale Implementation

The final result of the pilot studies should be to identify a recirculating ash sluicing system design which can be operated at the power plant. The system should be able to operate for long periods of time without scale formation in the slurry lines reducing performance. The design should include any monitoring equipment which may be necessary to minimize equipment failure and operating costs. The system should be designed to facilitate regular inspections at times when the power plant is undergoing routine maintenance.

This section discusses the kinds of equipment that may be used to build a recirculating ash sluicing system and discusses an implementation procedure.

3.4.1 Equipment

For some recirculating ash sluicing systems which sluice very reactive ash, many pieces of equipment may be necessary to safely operate the system. For others where the ash is essentially unreactive, only pumps and piping may be required. The former case will most likely exist in fly ash systems while the latter may exist for some bottom ash systems.

The least expensive piece of equipment that may be used to reduce the scaling potential of ash slurries is a reaction tank. The reaction tank should be large enough to allow the major portion of the leachable ions in the ash to enter the solution and allow controlled precipitation of any supersaturated species that may be formed due to the dissolution. The slurry can then be safely sluiced to the ash pond without danger of scale formation. The pilot studies should determine the minimum volume that will be required to obtain the necessary residence time.

In some systems the ash may be so reactive that controlled precipitation in the reaction tank may not be sufficient to eliminate scale and softening of the pond recycle may be necessary. The softener will reduce the levels of calcium and magnesium in the recycle water and reduce the relative saturation of $CaSO_4 \cdot 2H_2O$, $CaCO_3$ and $Mg(OH)_2$. The size of the softened stream should be determined in the pilot studies. The residence time in the flocculator should be at least 40-60 minutes and sedimentation requires 2-4 hours. The sludge produced by softening can be discharged into the ash pond.

A third treatment option that may be identified as a result of the pilot studies could be brine concentration. The level of dissolved solids in the slurry can be controlled with a blowdown stream. This stream can be treated with a brine concentrator which can supply the treated stream to other plant water consumers such [illegible] the boiler or cooling towers. The size of the blowdown [illegible] determined from pilot studies which will, in turn, [illegible] the size of the brine concentrator required.

3.4.2 Implementation

Once the system is built, full scale implementation should not present a problem. The major portion of the sluice water in a recirculating system is usually the pond recycle. The ash pond at most power plants has a very large residence time, on the order of one to four weeks. Thus, the pond water and, thus, the water quality of the sluice water will change very slowly toward its new "steady-state" value. Thus, the dampening effect of the pond should keep the system from experiencing drastic changes in operation. The system should be monitored very closely through the first month of operation to insure no drastic upsets occur which will cause scale formation.

4.0 SO_2/PARTICULATE SCRUBBING

Previous plant studies under this contract showed that combined SO_2/particulate scrubbing systems may be operated in a closed-loop mode to minimize makeup water requirements and eliminate aqueous discharges. These studies also identified the opportunity for reusing water discharged from other major water systems as makeup water to a combined SO_2/particulate scrubbing system. To minimize plant water requirements and discharges, the overall plant water system may be cascaded with the scrubbing system being the final step. Scrubbing systems typically do not require the good water quality that a cooling tower does. Cooling tower blowdown is therefore one candidate for use as scrubber makeup in a cascaded plant water system. For plants with wet ash handling, ash pond overflow may be another candidate.

The plant studies identified two potential problem areas associated with using cooling tower blowdown or ash pond overflow. First, if the scrubber makeup water is near saturation with respect to gypsum, scaling problems may be encountered when this water is used in the demisters. The amount of SO_2 sorbed in the demister and the amount of $CaCO_3$ solids entrained in the scrubber exit gas as well as the demister wash rate determine if scaling is likely.

The second problem area identified involves the dissolved solids concentration of the makeup water. The evaporation from the scrubbing system causes the makeup water to be concentrated. If the TDS level of the makeup is high, excessive TDS levels (>20 wt. %) in the scrubbing liquor may result. Excessive TDS levels can increase the energy requirements for pumping and decrease the mass transfer in the scrubber. If the alternate makeup source is high in chlorides, an excessive chloride concentration may result in the scrubbing liquor which may cause ocrrosion problems.

These recycle/reuse opportunities were identified for "throwaway" scrubbing systems where a waste sludge is produced and disposed of in a pond system. Some scrubbing systems are used for SO_2 removal only. These systems may be "throwaway" or "regenerative". Regenerative systems recover the sorbed SO_2 as $SO_2(\ell)$ or $H_2SO_4(aq)$ and recycle the alkali as opposed to dispsoing of the sorbed sulfur as calcium sulfite or calcium sulfate sludge. There is opportunity for recycle/reuse in regnerative systems as well as throwaway systems. In most cases regenerative systems require prescrubbers to prevent contaminant buildup in the system, and recycle/reuse options may be used in these prescrubber sections.

In regenerative SO_2 scrubbing systems very little water is required as makeup to the main scrubbing loop. This is because no sludge is produced in which water is occluded and little or no water is evaporated in the scrubber. The gas entering the main scrubber in most regenerative systems is near saturation with respect to water since a prescrubber or quench is normally used to remove particulates and chlorides from the flue gas upstream of the main scrubbers. Since very little water is lost in the main scrubbing loop, the concentrations of particulates and chlorides will build to intolerable levels if they are not removed by a prescrubber.

The procedure to test and implement the use of cascaded water in these prescrubber systems is the same as for throwaway systems and is discussed in this section. Emphasis will be placed on throwaway processes, however, since these types of systems were studied in detail in the previous studies conducted under this contract.

The four phases to implement a water recycle/reuse shceme for the major water systems of a coal-fired power plant were discussed in Section 1.0. These are:

Phase I - System Characterization

Phase II - Alternative Evaluation

Phase III - Pilot-scale Studies

Phase IV - Full-scale Operation

The first phase involves gathering design data to characterize the scrubbing system. It also includes a sampling program to supplement the design data. Since scrubbing systems are subject to operating variations from design, the sampling will help identify the effects of these variations. Sampling is also recommended for determining demister operating variables.

The second phase involves evaluating the feasibility of various alternatives. The design and operating data collected in the first phase can be used as the basis for performing process calculations to evaluate the feasibility of changing from open-loop to closed-loop or of changing makeup sources. These evaluations involve determining demister scale potential and scrubbing liquor composition. Calculations should accurately predict TDS levels in the system but pilot studies in addition to calculations are recommended to evaluate demister operation.

The third phase of implementation is to conduct pilot studies to evaluate alternative feasibility. Pilot studies will allow an evaluation of scale potential in the demister. Since the factors which affect demister scale potential (SO_2 removal, carryover, wash rate) are not easily measured, pilot studies should be conducted to assess the affects of process modifications. The fourth phase is to use the pilot study results to design and start-up the full-scale modifications.

The plant studies conducted in this program involved the first two phases of an implementation plan. Design and operating data for two combined SO_2/particulate scrubbing systems was collected and used to evaluate operation under existing and alternative conditions. Implementing the alternatives studied at the existing plants would require additional studies to evaluate demister operation and to better define variations in operating parameters.

The following discussions are written to apply to a general throwaway scrubbing system. All phases of an implementation plan are presented although the characterization and evaluation phases were addressed in the plant studies. Since virtually all scrubbing systems are unique with respect to operating conditions, a detailed characterization and evaluation phase should be conducted before implementing an alternative at a particular site. The purpose of the plant studies was to identify and evaluate the types of recycle/reuse alternatives achievable at coal-fired power plants. The purpose of this document is to outline a procedure for implementing the types of alternatives identified in the plant studies.

4.1 Phase I: System Characterization

The first phase in implementing a recycle/reuse scheme for a particular scrubbing system is to characterize the system operation. This includes collecting all design and operating data available and supplementing this data by collecting samples of the important process streams. This section first discusses the design and operating data required to characterize the system and then presents a sampling program to obtain additional data.

4.1.1 Identification of Process Variables

The design and operating data necessary to characterize a scrubbing system can be divided into three areas. These areas represent the three major operations in a typical SO_2/particulate scrubbing operation:

1) gas scrubbing and demisting,

2) solids precipitation, and

3) solids concentration.

Figure 4-1 is a simplified block diagram which shows how these three operations are combined. The gas is contacted with a recirculating slurry in the scrubber section where the particulates and SO_2 are removed. Demisters are generally used to minimize entrainment of the scrubbing liquor in the clean gas. The absorbed SO_2 is precipitated as solid calcium sulfite and/or calcium sulfate in the reaction tank. Concentration of the precipitated solids and the sorbed ash is achieved in the solid/liquid separation section. This concentration is made by a clarifier, filter, pond or a combination of the three. This section discusses the design data for each of these portions of an SO_2/particulate scrubbing systems that is required to characterize the system. All the data requirements discussed in this section should be easily obtained from the design specifications submitted to the utility by the scrubber manufacturer.

4.1.1.1 Scrubber and Demister Data

Table 4-1 is a data sheet listing the most important design data needed to characterize the scrubber and demister operations of a particular SO_2/ash scrubbing system. The first items listed in Table 4-1 for the scrubbers are the flue gas flow, temperature, and composition. The flue gas characteristics affect the amount of SO_2 and ash removed and the amount of water evaporated in the scrubbers.

The makeup water required for a scrubbing system is determined by the evaporation rate and the water lost by occlusion with the solid waste (ash, $CaSO_3 \cdot \frac{1}{2}H_2O$, $CaSO_4 \cdot 2H_2O$). The amount of solid waste generated, and, therefore, the occluded water lost, decreases with decreases in the amount of SO_2 and ash removed in the scrubbers. As the flue gas flow, SO_2 content, or ash content is decreased and the sludge percent solids increased, the makeup water required by the scrubbing system will decrease.

The design flue gas characteristics for various plant loads are therefore very important in determing the applicability of a particular water recycle/reuse option involving the scrubbing system. The makeup water requirement of the scrubbing

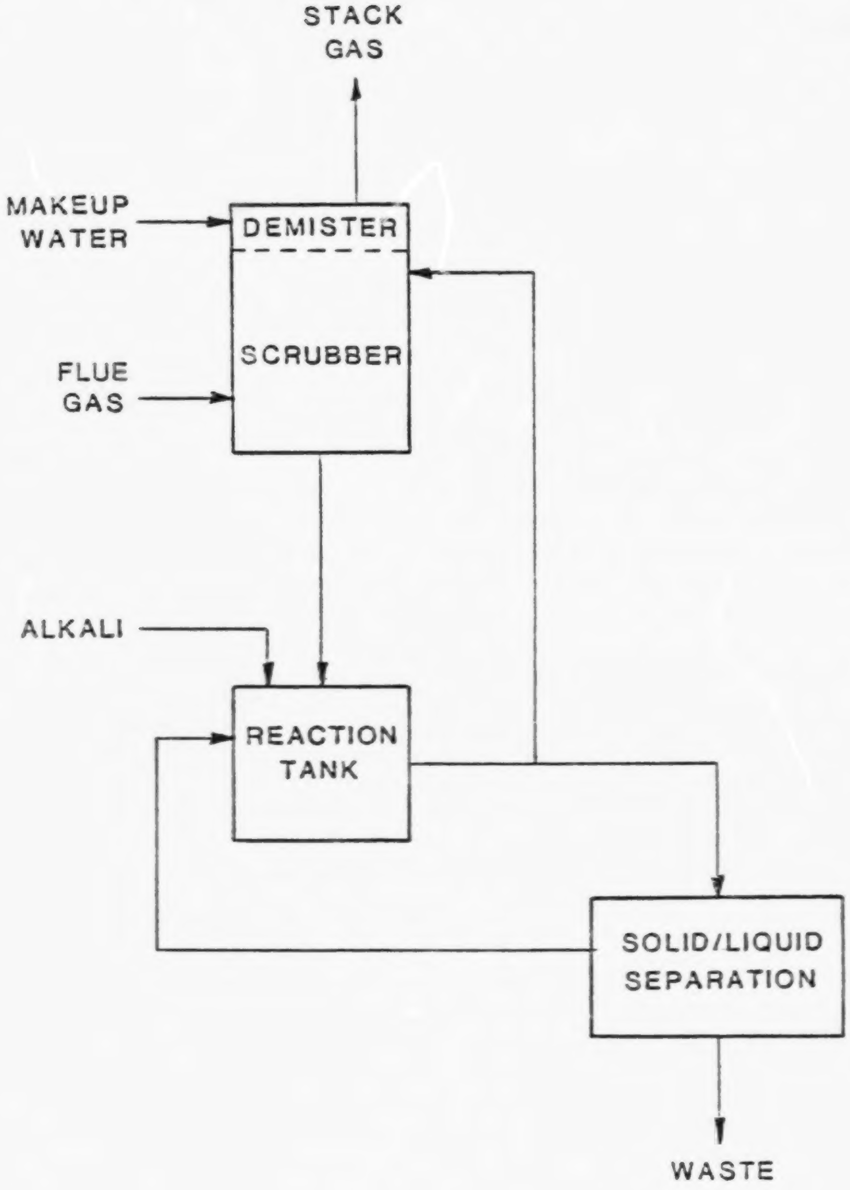

STACK GAS
MAKEUP WATER
DEMISTER
SCRUBBER
FLUE GAS
ALKALI
REACTION TANK
SOLID/LIQUID SEPARATION
WASTE

Figure 4-1. Typical scrubbing system flow scheme.

TABLE 4-1. SCRUBBER AND DEMISTER DATA

I. Scrubbers

A. Design Flue Gas

Flow (wet gas excluding ash) _____ lb/hr

Temperature _____ °F

Composition

N_2 _____ vol %

O_2 _____

CO_2 _____

SO_2 _____

HCl _____

H_2O _____

Ash loading into scrubbers _____ gr/scfd

B. Fly Ash Removal Stage

Liquid-to-gas ratio _____ gal/1000 acf (outlet)

Design Removal _____ %

C. SO_2 Removal Stage

Scrubber Type (spray tower, marble bed, etc.) _____

Liquid-to-gas ratio _____ gal/1000 acf (outlet)

Design Removal _____ %

II. Demisters

A. Once-through or recirculating loop _____

if recirculating:

makeup rate _____ GPM

blowdown rate _____ GPM

tank volume _____ gal

B. Wash Rate _____ GPM

C. Wash water source (fresh makeup, clarifier overflow, etc.) _____

D. Rate of scrubbing liquor entrained with the gas entering the demister _____ GPM system will determine the mode of operation of the water system supplying the scrubber makeup in a cascaded system. This is especially important in cases where zero discharge is desirable. For example, if cooling tower blowdown is used exclusively as scrubber makeup, the flue gas characteristics determine the tower blowdown rate and thus the cycles of concentration in the towers.

The design parameters for the fly ash and SO_2 removal stages affect the amounts of ash and precipitated solids disposed of and therefore the water lost by solids occlusion. Although evaporation accounts for most of the water lost in closed-loop scrubbing systems, the effects of ash and SO_2 removal efficiency should not be ignored. A more detailed discussion of the parameters affecting scrubber makeup water requirements may be found in the section concerning the plant studies conducted in this project.

The design parameters in Table 4-1 for characterizing the demister section of a scrubbing system include the system type (once-through or recirculating), the wash rate, the wash water quality, and the carryover rate. Makeup water is normally used wholly or in part as demister wash or demister wash makeup. The feasibility of using cascaded water for scrubber makeup water in the demister will depend on the demister characteristics as well as the cascaded water quality. The amount of SO_2 sorbed and the degree of $CaCO_3$ dissolution that occurs in the demister can be large enough to cause significant scaling, especially if the wash water is already high in dissolved calcium and sulfate. $CaCO_3$ solids are introduced into the demister loop by scrubbing liquor entrainment in the gas entering the demister.

Both once-through and recirculating demister wash operations may be used depending on the wash water requirements and the total scrubbing system makeup water requirement. If more water is required for demister wash than for the system makeup, a recirculating system must be used. A recirculating system uses a catch tray to collect most of the demister wash before it falls through the scrubber, whereas a once-through demister wash system allows the demister wash water to fall through the scrubber. A recirculating system will be more susceptible to scaling problems and therefore will require pilot studies to determine if a cascaded water may be used as demister wash. A possible solution is to use a combination of cascaded water and fresh makeup water as demister wash.

4.1.1.2 Reaction Tank Data

Table 4-2 presents the design data which characterize the solids precipitation section of a lime or limestone based scrubbing system. A reaction tank is used to control $CaSO_3 \cdot \frac{1}{2}H_2O$ and $CaSO_4 \cdot 2H_2O$ scale potential by allowing these solids to precipitate on recirculated seed crystals. The makeup alkali and some makeup water are added to the reaction tank. The alkali dissolves and combines with the sorbed sulfur to form calcium sulfite and/or calcium sulfate solids.

The additive type, composition, and addition rate will affect the liquid phase concentrations of calcium and magnesium in the system and therefore affect the calcium sulfite and calcium sulfate relative saturations encountered. The design parameters for the additive are therefore important in characterizing the solids precipitation section of a scrubbing system.

The type of water used to slurry the additive as well as the additive type will determine the scale potential in the alkali addition system. The use of waters saturated or near saturation with respect to $CaCO_3$ or $CaSO_4 \cdot 2H_2O$ may result in scale formation of one or both of these two species when some of the additive dissolves. This is especially important for lime systems where additive dissolution is fast.

The reaction tank volume and slurry solids content are included in Table 4-2 and affect the precipitation rate. Increases in slurry solids content and the reaction tank volume for a given precipitation rate lowers the relative saturation of the precipitating species. The required precipitation rates are determined by the amount of SO_2 sorbed in the scrubber and the oxidation occurring in the system. Higher oxidation causes the required precipitation rate of $CaSO_4 \cdot 2H_2O$ to increase but lowers the required $CaSO_3 \cdot \frac{1}{2}H_2O$ precipitation rate.

The final item in Table 4-2 is the rate and composition of makeup water added to the reaction tank. The quality of the makeup water will affect the dissolved solids content of the liquor in the scrubbing system but was shown to have little effect on scale potential in the system in the plant studies performed in this project. The chloride content of the makeup water is important since this affects the chloride concentrations in the system and may cause corrosion problems if the level is too high. The chloride content of a cascaded water used as scrubber makeup is therefore an important parameter to consider in a water recycle/reuse scheme.

TABLE 4-2. REACTION TANK DATA

I. Alkali Additive

A. Type (lime, limestone) _____

B. Composition

Lime

CaO or $Ca(OH)_2$ _____ wt. %

MgO or $Mg(OH)_2$ _____

Inerts _____

Limestone

$CaCO_3$ _____ wt. %

$MgCO_3$ _____

Inerts _____

C. Addition rate _____ lb/hr

D. Water Source for slurrying additive (makeup, clarifier overflow, etc.) _____

II. Tank

A. Volume _____ gal

B. Slurry suspended solids content _____ wt. %

C. Makeup water added to tank

Flow _____ GPM

Composition (design basis)

Calcium _____ mg/ℓ

Magnesium _____

Sodium _____

Chloride _____

Sulfate (as $SO_4^=$) _____

Nitrate (as NO_3^-) _____

4.1.1.3 Solids Concentration Data

Table 4-3 presents the design information necessary to characterize the solids concentration section of a scrubbing system. This data is divided into two parts. The first part concerns the clarifier and filter which may or may not be present in every system. In some cases, the blowdown from the scrubbing loop is pumped directly to the pond or diluted with pond liquor and pumped to the pond. In these cases, additional data concerning mixing tank volume and solids concentrations of all streams is required to characterize the system. The second portion of the data in Table 4-3 is for the pond system where the waste solids (ash, $CaSO_3 \cdot \frac{1}{2}H_2O$, $CaSO_4 \cdot 2H_2O$) are deposited.

The solids concentration section of a scrubbing system determines whether the overall system is closed or open-loop. In a closed-loop system all water not occluded with the settled sludge or evaporated in the pond is recycled to the scrubbing system. The design flow rates and suspended solids concentrations of all of the streams in the solids concentration section of a scrubbing system are necessary to fully characterize the system. The effects on the operation of this section of converting from open-loop to closed-loop system design should be evaluated for this type of recycle/reuse opportunity. Changes in oxidation resulting from process modifications may have a significant effect on solid/liquid separation equipment. Calcium sulfite crystals are platelets and do not tend to settle as easily as calcium sulfate solids. Careful consideration of these effects should be made before a recycle/reuse alternative is implemented.

4.1.2 Sampling Plan

Although design data provides a great deal of information concerning system characterization, a sampling program is necessary to supplement this data. Actual operation will deviate from design condidtions with changes in coal composition, water composition, additive composition, and load. Since these four parameters are continuously fluctuating, a sampling program to characterize system operation under actual conditions is necessary. Also, demister operation may be more fully characterized with a sampling program. Material balances around the demister loop may be performed using sample data to determine SO_2 removal and carryover in the demister.

Two general types of measurements should be made in a characterization sampling program. These are analytical and

TABLE 4-3. SOLIDS CONCENTRATION DATA

I. Clarifier/Filter (if applicable)

A. Feed rate _____ GPM
B. Bottoms suspended solids _____ wt. %
C. Overflow suspended solids _____ ppm

II. Pond System

A. Number of Ponds _____
B. Surface area of each pond
_____ acres
_____
_____
_____
C. Settled sludge (bottom of pond) solids concentration _____ wt. %
D. Pond overflow rate _____ GPM
E. Pond overflow suspended solids _____ ppm
F. Pond overflow recycled to scrubbing system _____ GPM
G. Pond overflow discharged _____ GPM

process measurements. Analytical measurements can be used to characterize the chemistry of the scrubbing system by determining solids precipitation rates, SO_2 removal rate, SO_2 oxidation, and scaling potentials. Process measurements can be used to characterize the system water balance for different operating conditions by determining flow rates for key process streams and levels for major process tanks.

4.1.2.1 Analytical Measurements

Chemical analysis and sampling schedules can be divided into two categories, each serving a different function. These categories are system characterization measurements and line-out measurements. System characterization samples should be taken after sufficient time is allowed for the system to reach steady-state operation. Steady-state operation is determined from the line-out measurements. When the system has reached steady-state, the stream compositions will not change appreciably between sample periods.

The characterization sample points and analyses for a typical scrubbing system with a recirculating demister wash system as shown in Figure 4-2 are presented in Table 4-4. The analyses to be performed on these samples are divided into three categories: gas analyses, liquid analyses, and solids analyses. Gas analyses on the flue gas and stack gas for SO_2, CO_2, O_2, H_2O, and HCl will determine the SO_2 removal rate, HCl removal rate, and the evaporation rate in the scrubbers.

Liquid analyses are shown in Table 4-4 for the remaining sample points. It should be noted that some deviation from the sampling plan shown in Table 4-4 should be expected for a particular scrubbing system. If a system uses a once-through demister wash with makeup water, sample points 10 and 11 may be eliminated. Also, if a clarifier is not used, sample points 7 and 8 may be eliminated.

Not all of the liquid analyses listed in Table 4-4 necessarily need to be made for each sampling period. Some variables, such as the magnesium, sodium, nitrate, and chloride liquor concentrations, should not change significantly under normal operation. Changes in makeup water quality, alkali additive, coal composition, or load are the major factors influencing the magnesium, sodium, nitrate, and chloride levels. Whenever step changes in these variables are made, complete liquor analyses should be made until the system is at steady-state (line-out measurements).

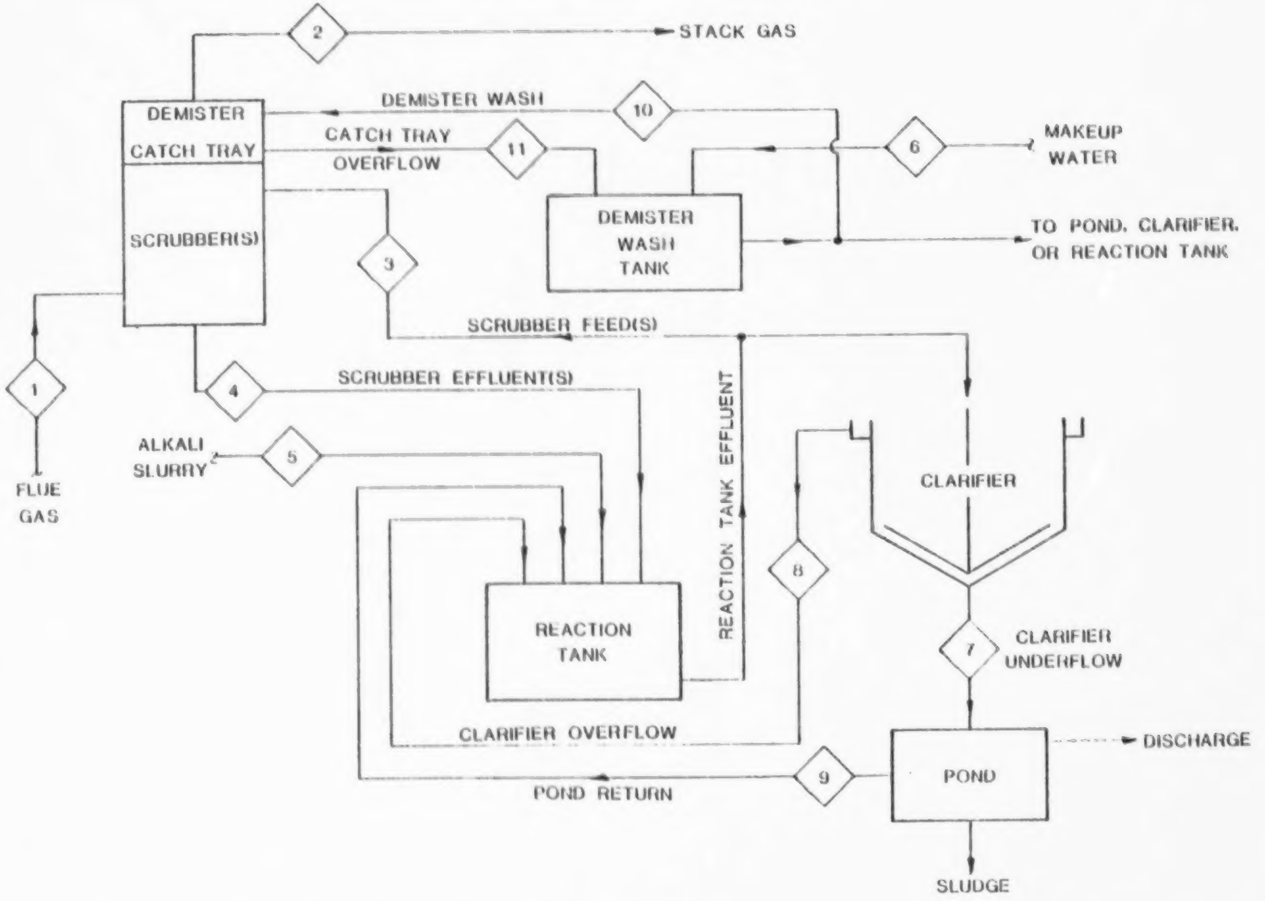

STACK GAS
DEMISTER
CATCH TRAY
SCRUBBER(S)
DEMISTER WASH
CATCH TRAY
OVERFLOW
MAKEUP
WATER
DEMISTER
WASH
TANK
TO POND, CLARIFIER,
OR REACTION TANK
SCRUBBER FEED(S)
SCRUBBER EFFLUENT(S)
REACTION TANK EFFLUENT
ALKALI
SLURRY
FLUE
GAS
CLARIFIER
REACTION
TANK
CLARIFIER
UNDERFLOW
CLARIFIER OVERFLOW
DISCHARGE
POND RETURN
POND
SLUDGE
1
2
3
4
5
6
7
8
9
10
11

Figure 4-2. Sample points for scrubbing system characterization.

02-2210-1

TABLE 4-4. SCRUBBING SYSTEM CHARACTERIZATION MEASUREMENTS SAMPLE POINTS AND ANALYSES

	Sample Point No.	Gas Analyses					Liquid Analyses								Solids Analyses					
		SO_2	CO_2	O_2	H_2O	HCl	Ca	Mg[1]	Na[1]	Cl[1]	CO_2	NO_3[1]	SO_2	Total S	% Solids	Ca	Mg	CO_2	SO_2	SO_3
Flue Gas	1	X	X	X	X	X														
Stack Gas	2	X			X	X														
Scrubber Feed(s)	3						X	X	X	X	X	X	X	X	X	X	X	X	X	X
Scrubber Effluent(s)	4						X	[X	X	X]^2	X	[X]^2	X	X	X	[X	X	X	X	X]^2
Alkali Slurry	5						X	X	X	X	X	X	X	X	X	X	X	X		
Makeup Water	6						X	X	X	X	X	X	X	X						
Clarifier Underflow[4]	7						X	[X	X	X]^2	X	[X]^2	X	X	X	[X	X	X	X	X]^2
Clarifier Overflow[4]	8						X	[X	X	X]^2	X	[X]^2	X	X	X					
Pond Return	9						X	[X	X	X]^2	X	[X]^2	X	X	X					
Demister Wash[5]	10						X	X	X	X	X	X	X	X	X	X	X	X	X	X
Catch Tray Overflow[5]	11						X	[X	X	X]^3	X	[X]^3	X	X	X	X	X	X	X	X

[1] These analyses should be performed periodically since they should not change rapidly.

[2] These analyses can be deleted if differences between these points and sample point 3 are negligible.

[3] These analyses can be deleted in differences between this point and sample point 10 are negligible.

[4] These sample points may be eliminated for systems which do not use clarifiers or thickeners.

[5] These sample points may be eliminated for systems which use once-through demister wash with makeup water.

Solids analyses are shown in Table 4-4 for the scrubber feed, scrubber effluent, alkali slurry, clarifier overflow, demister wash, and catch tray overflow streams. In addition, total suspended solids analyses are shown for the clarifier overflow and pond return streams.

To characterize a scrubbing system, a sampling program should last from 1-2 weeks for a given set of operating conditions to allow complete system line-out. The actual time required will depend on the stability of the operating variables and the process design. Larger reaction tank residence times will require a longer period of time for the system to reach steady-state. Line-out samples to determine if the system is at steady-state should be taken twice daily.

The cost for conducting such a sampling program will vary directly with the length of the sampling program and the number of sampling points and analyses to be made. Meaningful cost estimates for a characterization sampling program can only be made for a specific system after a detailed program is outlined. The addition of sampling ports and/or laboratory capabilities at a specific site should be considered as well as the manpower requirements and the number of samples and analyses to be made.

4.1.2.2 Process Measurements

In order to properly characterize the performance of a scrubbing system, certain process measurements must be gathered in conjunction with the chemical analyses discussed in the previous section. These process measurements include such variables as liquor flow rate, flue gas flow rates, various tank levels, and important stream pH's and temperatures. Table 4-5 indicates which process measurements are required for system characterization purposes.

Several of the desired flow rates may be monitored on a regular basis by plant personnel. These may include scrubber feed, clarifier feed, and alkali additive. Before starting a sampling program all existing flow meters should be calibrated by using variations in tank levels with time. Periodic calibrations of flow meters should be made throughout a sampling program.

TABLE 4-5. PROCESS DATA REQUIREMENTS

Stream Name	Flow Rate	Pressure	pH	Temperature
Gas Streams				
Flue Gas	X	X	-	X
Stack Gas	-	X	-	X
Liquid Streams				
Scrubber Feed	X	-	X	X
Scrubber Bottoms	-	-	X	X
Clarifier Feed	X	-	X	X
Clarifier Overflow	X	-	X	X
Reaction Tank Effluent	X	-	X	X
Pond Return	X	-	X	X
Alkali Slurry	X	-	X	X
Makeup Water	X	-	X	X
Demister Wash	X	-	X	X
Catch Tray Overflow	-	-	X	X
Demister Wash Loop Blowdown	X	-	X	X

Tank Level Data

Vessel	Level
Additive Tank	X
Reaction Tank	X
Demister Loop Tank	X
Surge Tanks	X

Important streams whose flows are not already monitored should be included in a comprehensive characterization program. The flue gas rate can be measured with a pitot tube placed in the scrubber gas feed duct. Necessary correlations of flow rate *versus* pitot reading can be generated by performing periodic pitot traverses of the gas duct. This measurement should be made as close to the scrubber inlet as possible to minimize errors due to leakage.

Slurry stream flow rates may be monitored by magnetic flow meters. Additional flow meters should be obtained for slurry streams whose flows are not already monitored in the scrubbing loop (scrubber feed, clarifier feed, reaction tank effluent, demister wash loop blowdown). The flow meters can be used for the pilot studies discussed in Section 4.3 as well as for the system characterization phase.

Water makeup streams (to pump seals or demister wash tank) should be equipped with rotameters. The rotameters (both existing and new) should be calibrated before starting the characterization sampling. Intermittent flows such as periodic washing of the catch tray may be characterized by noting the frequency of washing.

The flows around the clarifer and pond are not as critical as the streams previously discussed for purposes of characterizing scrubbing system operation. Solids balances and pump characteristics can be used to estimate clarifier underflow, clarifier overflow, and pond return rates. The combined flow of these three streams is normally small in comparison to other streams entering the reaction tank. For this reason, any errors resulting from imprecise flow measurement of these streams will have a negligible effect on material balances performed around the reaction tank.

Temperature and pH measurements are listed for all of the liquid streams in Table 4-5. This should be done routinely as a part of the sampling procedure. Stream temperatures within the scrubbing loop should remain relatively constant. Some heat losses occur through pipe and open vessels, however. Initially all stream temperatures should be recorded. As the sampling program proceeds, it may be possible to omit some temperature measurements if only small differences exist.

Tank levels should be recorded routinely. In combination with water makeup rates, the slurry levels of the larger vessels will determine the magnitude of the system's water requirements. Increases or decreases in tank slurry levels will affect the calculation of water evaporation and addition rates through material balances.

4.2 Phase II: Alternative Evaluation

The second phase of a scrubbing implementation plan is to formulate and evaluate various modes of operation. Formulation of alternative operating conditions will depend on how the scrubbing system fits into the overall plant recycle/reuse scheme. The plant studies conducted in this program showed that alternatives include converting from open-loop to closed-loop operation and changing makeup water source. Alternative makeup water sources may include cooling tower blowdown or ash pond overflow.

To determine the feasibility of implementing a recycle/reuse alternative, both potential scale formation in the demister and the TDS level (including chlorides) of the scrubbing liquor should be investigated.

The plant studies portion of this project showed that an effective tool for performing alternative evaluations is a process simulation computer model package. A process simulation package can also be used to evaluate the consistency of the data collected in the system characterization phase of an implementation plan. This section first discusses the calculations required to evaluate scrubber alternatives and then presents a methodology for using a model to perform the evaluations.

4.2.1 Evaluation Criteria

The scrubbing evaluation should involve mass and energy balances to calculate flows, compositions, and temperatures of all process streams. An overall material and energy balance includes a humidification calculation to determine the amount of water evaporated by the flue gas, and a prediction of solid-liquid equilibrium for the solid waste. The important solid-liquid equilibria include $CaCO_3$, $CaSO_4 \cdot 2H_2O$, and $CaSO_3 \cdot \frac{1}{2}H_2O$. Of the remaining material balances, calculations around the scrubber, demister, and reaction tank are the most important. The balances around the solid-liquid separation portion of a scrubbing system are simple material balances based on the known solids flow calculated by the overall balance and the suspended solids concentrations of all the streams. Calculations around the scrubbing vessel include the prediction of gas-liquid equilibria between the CO_2 and SO_2 in the gas and liquid streams in the scrubber. A common assumption for CO_2 is that CO_2 is transferred between the scrubbing liquor and the gas so that the liquor equilibrium partial pressure of CO_2 is equal to the CO_2 partial pressure in the gas. A scrubbing process evaluation should include this equilibrium so that the amount of CO_2 entering or leaving the system through the scrubber may be determined.

The evaluation should also include prediction of the equilibrium partial pressure of SO_2 above the scrubbing liquor. Calculation of this parameter will allow an evaluation of the ability of a given scrubbing liquor to remove a specified amount of SO_2 from the flue gas. Any changes in liquor composition resulting from the implementation of a recycle/reuse scheme may be evaluated in terms of SO_2 removal capability by comparing liquor equilibrium SO_2 partial pressure to the outlet gas SO_2 partial pressure. The prediction will allow an estimate of the SO_2 removed in the demister to be evaluated. The partial pressure of SO_2 above the demister wash should be less than the partial pressure of SO_2 in the stack gas.

The calculations outlined above will allow a particular scrubbing recycle/reuse option to be evaluated in terms of scale potential and dissolved solids content of the scrubbing liquor. The following sections present discussions of the prediction of scale potential and TDS levels in a typical scrubbing system.

4.2.1.1 Scale Potential

The most important factor which determines the feasibility of implementing a scrubbing recycle/reuse alternative is the potential for scale formation in the demister. If significant scale deposits form, the system must be shut down for cleaning.

In the plant studies portion of this study, the concept of relative saturation was used to predict scaling potential. When the relative saturation of a species is below 1.0, no potential for solids precipitation exists. When the relative saturation is greater than 1.0, the species is supersaturated and scale may form. In the presence of seed crystals, the relative saturation may exceed 1.0 without scale formation. However, as relative saturation increases above 1.0, a critical value is reached where nucleation occurs. When this happens, scaling may occur since conditions favorable to the creation of new crystal nuclei also tend to produce scale.

Past experience has shown that calcium sulfate dihydrate will form chemical scale when its relative saturation reaches 1.3-1.4. A scaling limit also exists for calcium sulfite hemidydrate, but it is not as well defined as the limit for gypsum. A value of at least three to four times the sulfite saturation level (R.S. = 1.0) is necessary to initiate sulfite scaling. Some systems have been reported to operate at six to seven times the sulfite saturation value without scaling. A detailed definition of relative saturation was given in Section 2.2.1.1.

If a recirculating demister wash system is used, the evaluation of potential scale formation in the demister should include a prediction of solid precipitation and dissolution rates in the demister wash tank. The concept of relative saturation may be used to calculate rates as follows:

$$R = KafCV\,(R.S. - 1)$$

where

R = precipitation or dissolution rate

K = a temperature dependent constant

a = crystal interfacial area

f = weight fraction of the considered species in the solid phase

C = total suspended solids concentration

V = tank volume

R.S. = relative saturation of considered species

It is important that the scrubbing process evaluation include rate calculations and determination of the relative saturations of important species in the system. The effects of process modifications must be evaluated in terms of these parameters to insure that implementation of a water recycle/reuse option will not result in scale formation in the demister.

4.2.1.2 Dissolved Solids Concentration

If the scrubber makeup water is high in dissolved solids, excessive TDS levels in the scrubbing system may be encountered. The water evaporated in the scrubbing system causes the dissolved solids in the makeup water to be concentrated in the scrubbing loop.

Excessive TDS levels in the scrubber liquor can increase the energy requirements for pumping the liquor and can decrease the mass transfer characteristics in the scrubber. As the TDS level increases, the viscosity of the scrubbing liquor will increase. For example, the viscosity of a 25 wt. % NaCl solution is about twice that of pure water while a 5 wt. % solution has a viscosity only about 10% higher than pure water. As the viscosity of the scrubbing liquor increases, the energy requirements for pumping the liquor will increase.

The TDS level will also affect the surface tension of the liquor. Excessive TDS levels may cause larger droplet sizes in a spray tower. This may reduce the mass transfer characteristics of the droplets and adversely affect scrubber performance.

The level of chloride present in the makeup water may also limit the use of an alternate makeup source in a scrubbing system. If the chloride level in the scrubbing liquor is too high, corrosion problems may be encountered.

The material and energy balances discussed previously will allow prediction of the TDS and chloride levels expected under alternate operating conditions. The limitations discussed here should be considered in evaluating the feasibility of converting to closed-loop operation or of changing makeup water source.

4.2.2 Model Application

As part of a recycle/reuse implementation plan, a process model may be used for two purposes:

1) check consistency of data obtained in characterization phase, and

2) evaluate and optimize alternative operating conditions.

The data collected both from design information and the sampling program can be used as inputs to the model to calculate makeup water requirements, precipitation rates, and scaling potentials in the system. The values determined by the model may then be compared to the measured values obtained from the sampling program to check the data consistency and the validity of the process model. In addition to comparing stream compositions and pH's, the calculated equilibrium SO_2 partial pressure above the scrubber effluent stream should be compared to the measured SO_2 partial pressure in the stack gas. If the measured stack gas SO_2 concentration does not exceed the calculated SO_2 equilibrium partial pressure, a gas or liquid phase anlaytical error is indicated. In this case, the analytical data should be re-examined.

Once the data consistency checks have been made and the process model has been verified, simulations of the scrubbing system under alternative operating conditions should be made. Alternative simulations should be performed for a variety of conditions under which the scrubbing system is expected to operate. These should include different loads and different coal compositions as well as variations in makeup water quality. The design and operating data collected in the characterization phase of the implementation plan should be used to identify the magnitude of variations expected for the scrubbing system.

Simulations for both typical operation in the alternative mode and for worst case operation should be made. In the case where cooling tower blowdown or a combination of fresh makeup water and cooling tower blowdown is being considered as scrubber makeup water, several simulations should be performed to optimize the system configuration or ratio of fresh water to cooling tower blowdown. This is particularly important for scrubbing operations with recirculating demister wash systems. The level of SO_2 removal, oxidation, and carryover in the demister section should be investigated with simulations to determine the long-term effects of these parameters on system operation.

In addition to investigating long range variations in operating conditions, simulations to determine the effects of short-term upsets should be made. Short-term upsets may include changes in SO_2 removal, oxidation, flue gas temperature, and makeup water quality. For example, in a cascaded water system where cooling tower blowdown is used as scrubber makeup, any upsets which occur in the cooling system will cause a change in the scrubber makeup water quality.

The results of these simulations should identify operating conditions which can be expected under a recycle/reuse alternative. Stream temperatures, flows, and compositions will be specified by the model and should allow evaluation of the feasibility of the recycle/reuse option with respect to system scaling potential and TDS levels. The simulation results may be used as a basis for designing and process modifications or for designing a detailed test program for further investigations on a pilot or prototype scale. The number of simulations required and therefore the cost of performing the simulations will depend upon the type of modifications considered and the stability of the particular system under consideration. If the scrubbing system is subject to wide variations in operating conditions, more simulations should be performed to fully evaluate the effects of instituting a water recycle/resue option. Meaningful cost estimates can only be made for a particular system undergoing a specific recycle/reuse modification(s).

4.3 Phase III: Pilot-Scale Studies

After the characterization and simulation phases of an implementation plan have been completed, pilot-scale testing should be performed to further analyze the effects of the water recycle/reuse scheme on scrubber operation. Two types of scrubbing system modifications have been identified as parts of a plant water recycle/reuse scheme. These are converting from open-loop to closed-loop operation and using a cascaded water stream as scrubber makeup. This section discusses each of these two types of scrubber modification separately.

4.3.1 Converting to Closed-Loop Operation

One method identified for minimizing the water requirements of a SO_2/particulate scrubbing system is to operate the system in a closed-loop mode. In a closed-loop system all the excess water leaving with the solid waste is recycled to the scrubbers. The only water lost with the solids will be that occluded with the sludge. If a pond is used, the sludge will be about 50% water. If a vacuum filter is used for solids concentration, the sludge may be as low as 35% water for systems with high oxidation (either forced by air sparging or naturally occurring).

Since scrubbing systems are not designed with a separate clarifier, filter, or pond for each module, the isolation of an individual module is not feasible for testing the effects of converting from open-loop to closed-loop operation. Either a pilot scale or one-module prototype installation is required to test closed-loop operation. Additional piping will be required to return the pond overflow for systems using a pond for solid/liquid separation. For scrubbing systems with high oxidation, a vacuum filter may be installed to effectively dewater the sludge to about 65% solids. Piping would then be necessary to return the filter supernatant to the system. Converting to closed-loop operation will lower the system makeup water requirements and, therefore, affect the demister water balance. If a once-through demister is used, additional water to supplement the decreased makeup can be taken from the clarifier overflow. If the evaluation phase showed this option not to be feasible, a recirculating demister system may be installed. This would involve adding a catch tray to the scrubber internals, a demister wash tank, and additional piping and pumps. The cost of the new equipment will depend on the size of the system and the particular process option chosen (once-through or recirculating demister).

Once the process modifications have been made, the pilot or prototype system may be started up. As with the characterization sampling scheme, line-out samples should be taken until the system has reached steady-state. The time required to reach steady-state will depend on the particular system design. Larger reaction tanks and the use of a pond will increase the system residence time and, therefore, require longer line-out time.

The sampling strategy outlined in Section 4.1.2 also applies to pilot testing. Closed-loop operation should be tested under a variety of conditions to insure safe operation with the modified system. These conditions will have been identified by the characterization phase as being likely to occur. Changes may involve variations in flue gas flow, SO_2 concentration, and makeup water composition.

As was illustrated in Table 4-4 of the characterization section, gas analyses are recommended for the flue gas entering the system and the stack gas leaving the scrubbing system. Complete liquor analyses are recommended for the makeup water, clarifier overflow, and pond return. Liquid and solid analyses are recommended for the scrubber feed, scrubber effluent, alkali slurry, clarifier underflow, and demister loop slurries. Liquid analyses should include calcium, magnesium, sodium, chloride, carbonate, nitrate, sulfite, and total sulfur. Solid phase analyses should include calcium, magnesium, carbonate, sulfite, and sulfate.

In many cases the soluble species (magnesium, sodium, chloride, and nitrate) may not change appreciably throughout the system since system liquid phase residence times are much shorter than solid phase residence times. If preliminary results indicate this, then some of the liquid phase analyses may be eliminated or performed less frequently. Notes to this effect are listed at the bottom of Table 4-4.

Operation of the pilot or prototype facilities in a closed-loop mode over the range of operating conditions to be expected on a full-scale will establish a strong basis upon which the full-scale modifications may be based. Effects on the scrubbing operation as well as the optimum demister configuration for closed-loop operation can be assessed with the results from the pilot or prototype studies.

4.3.2 Changing Makeup Water Source

As discussed previously for converting to closed-loop operation, isolation of an individual module of a scrubbing system may not be practical to study system modifications. Again, a one-module prototype or pilot-scale installation is ideal for testing this water recycle/reuse scheme.

Additional piping and a makeup water mixing tank will be required in order to study the use of a mixture of existing makeup water and an alternative source (cascaded water) as scrubber makeup. Using a mixture of makeup waters will allow the optimum level of use of cascaded water as makeup to be determined. It is recommended that four or five different ratios of makeup water sources be used and the scrubbing system chemistry be characterized under each condition. Scaling potential should be evaluated for the demister wash loop as well as for the main scrubbing loop of the system.

The sampling strategy outlined for the characterization phase of implementation may be used in this phase also. Sample points and analyses were tabulated in Table 4-4 of the characterization section.

The results of these pilot or prototype studies will allow the design of a full-scale modification to use cooling tower blowdown (or other cascaded water) or a mixture of the tower blowdown with fresh makeup water. The pilot studies will identify any process modifications necessary to prevent scaling in the demisters. They will also identify the optimum mixture of makeup waters to allow reliable system operation if the new makeup water source may not be used exclusively.

4.4 Phase IV: Full-Scale Operations

The final result of the pilot studies will be a system design which will allow closed-loop operation or substitution of an alternate makeup water source. Either one of these process modifications may require changing the demister loop design to prevent scale formation in the demister. Converting a once-through demister system to a recirculating system will involve installing a catch tray under the demister so that most of the wash water may be recycled. Additional tanks, pumps, and piping will also be required.

After the equipment modifications have been made, it is recommended that the system operation be monitored closely until steady-state is achieved. The same sampling strategy outlined in the characterization phase should be used to perform a final evaluation of the full-scale modified system. The frequency of sampling may be decreased somewhat since the line-out time required for a full-scale system using a pond will be significantly longer than a pilot or prototype installation using a vacuum filter. After reliable operation is established, a regular sampling program should be established to monitor system performance. This program will be especially important when the plant is undergoing a step change such as changing the type of coal fired or the system load.

5.0 SUMMARY

Generalized implementation plans have been presented for recycle/reuse alternatives identified in the plant studies conducted in the first part of this program. Recycle/reuse options were identified for cooling tower, ash sluicing, and SO_2/particulate scrubbing systems at coal-fired power plants.

Options for cooling towers included increased recirculation resulting in lower blowdown and makeup rates. Increased recirculation in cooling towers may require the addition of pH control with sulfuric acid or softening (either makeup or slipstream) to control gypsum scale potential. The implementation plan discussed was divided into three phases: 1) system characterization, 2) alternative evaluation, and 3) full-scale modifications. This plan presented methodologies for identifying operating variables and using these variables to evaluate scaling potential and treatment requirements for alternate operating conditions. The equipment and sampling requirements for implementing full-scale changes in cooling tower operation were also presented.

Recycle/reuse options identified for ash sluicing operations include converting to completely or partially closed-loop operation. These options may require treatment to prevent scaling. Possible treatments identified include 1) the use of a reaction tank to allow ash dissolution and solids precipitation to prevent scaling in the sluice line and 2) the use of softening to reduce the dissolved calcium in the pond recycle. A plan was presented whereby a recirculating ash sluice system may be implemented. Four phases were identified 1) ash characterization, 2) alternative evaluation, 3) pilot studies, and 4) full-scale operation. The first phase discussion presented a methodology for identifying ash reactivity with bench-scale experiments. The second phase presented a methodology for evaluating the feasibility of a recirculating system based on scale potential and treatment requirements. Pilot studies (third phase) were recommended for ash sluicing to better define operating parameters which are not easily predicted and to evaluate treatment options. The full-scale phase discussion included descriptions of equipment required and important operating variables.

For SO_2/particulate scrubbing systems, two potential recycle/reuse options were identified in the plant studies. These included converting to closed-loop operation and using an alternate makeup water source such as cooling tower blowdown or ash pond overflow. A general implementation plan has been presented for instituting these types of modifications. As with ash sluicing, four phases were identified: 1) system characterization, 2) alternative evaluation, 3) pilot studies, and 4) full-scale modifications. The first phase discussion presented the important operating variables to be considered and a sampling plan for obtaining operating data. The second phase presented a methodology for evaluating the feasibility of recycle/reuse options. The pilot studies (third phase) presented a plan for testing operation with a recycle/reuse option. Potential problem areas are demister scale formation and TDS level in the scrubbers. The full-scale discussion described the equipment necessary and recommended a sampling strategy to be used to monitor system performance.

REFERENCES

BA-465 Babcock and Wilcox Company, Steam, its generation and use, 37th ed., N.Y., 1955.

CH-335 Chu, Tien-Yung J., Peter A. Krenkel, and Richard J. Ruane, "Reuse of ash sluicing water in coal-fired power plants", in Proceedings of the Third National Conference on Complete Water Reuse: Symbiosis as a Means of Abatement for Multi-Media Pollution, Cincinnati, June 1976, Lawrence K. Cecil, ed., N.Y., AIChE, 1976.

DE-165 Derrick, A. E., "Cooling pond proves to be the economic choice at Four Corners", Power Eng. 1963 (Nov.), 46.

DI-057 Dickey, Joe Ben, Jr. and Robert E. Cates, Managing waste heat with the water cooling tower. 2nd ed. Mission, Kansas, Marley Co., 1973.

DI-170 Dionex Corporation, Analytical ion chromatography, Models 10 and 14, operation and maintenance manual. Palo Alto, CA, Jan. 1976.

EL-094 Electrical World Directory of Electric Utilities, 74-75, 93rd Edition. N.Y., McGraw-Hill, 1974.

FE-001 Feitknecht, W. and P. Schindler, "Solubility constants of metal oxides, metal hydroxides, and metal hydroxide salts in aqueous solution", Pure Applied Chem. 6, 130-160, 197-99 (1963).

FE-102 Federal Power Commission, *Steam-electric plant air and water quality control data for the year ended December 31, 1972*. Atlanta, Georgia, 1973.

FU-001 Fuoss, R. M., "Ionic association, pt. 3, the equilibrium between ion pairs and free ions", *J. ACS 80*, 5059-61 (1968).

GH-001 Ghosh, S. R., S. C. Ghosh and D. Roy, "Nitrogen Oxides Absorption. Design of Packed Towers", *Technology 2* (3), 149-59 (1965); *C. A. 65*: 3358d.

GJ-001 Gjaldbaek, J. K., "Untersuchungen uber die loslichkeit des magnesium-ydroxyds", II. Die loslichkeitsprodukte und die dissoziationskonstante der magnesium hydroxyde", *Z. Anorg. Chem. 44*, 259-88 (1925).

GU-075 Guthrie, K. M., *Process plant estimating evaluation and control*. Solana Beach, CA, Craftsman Book Co., 1974.

JA-105 Jaulmes, P. and S. Brun, "Solubilisation et precipitation des sels peu solubles d'acides moyens ou faibles", *Trav. Soc. Pharm. Mont. 25*(2), 98 (1965).

KL-052 Klein, David H., Melvin D. Smith, and James A. Driy, "Homogeneous nucleation of magnesium hydroxide", *Talanta 14*, 937-40 (1967).

KL-053 Klein, David H. and James A. Driy, "Heterogeneous and homogeneous nucleation of strontium sulphate", *Talanta 13*, 289-95 (1966).

KL-054 Klein, David H. and Louis Gordon, "Nucleation in analytical chemistry, II. Nucleation and precipitation of silver chloride from homogeneous solution", *Talanta 13*, 177-86 (1959).

LE-201 Leung, Paul and Raymond E. Moore, "Water consumption study for Navajo Plant", in *Proceedings of the American Society of Civil Engineers, Power Division, 97* (PO4), 8564 (1971).

LE-239 Lepper, F. R., Jr., Private communication, Resources Conservation Co., 3 June 1976.

LI-001 Linden, J. Van der, *J. Soc. Chem. Ind. 36*, 96 (1917).

LI-068 Linke, William F., comp., *Seidell's solubilities. Inorganic and metal-organic compounds*, 4th ed., 2 vols., Princeton, NJ, D. Van Nostrand, 1958, 1965.

MC-136 McGlamery, G. G., et al., *Detailed cost estimates for advanced effluent desulfurization processes*. Interagency Agreement EPA IAG-134 (D), Pt. A. Research Triangle Park, NC, Control Systems Lab., NERC, 1974.

NA-205 National Coal Association, *Steam-electric plant factors*, 24th ed., WAshington, D.C., 1974.

NE-107 Nelson, Guy R., Water recycle/reuse possibilities: *power plant boiler and cooling systems*, final report. EPA 660/2-74-089. Corvallis, Oregon, National Environmental Research Center, Thermal Pollution Branch, September, 1974.

OT-001 Ottmers, D. M., Jr., Simulation of NAPCA venturi system. Technical Note 200-002-4, Austin, Texas, Radian Corporation, November 1969.

PA-121 Patterson, W. C., J. L. Leporati, and M. J. Scarpa, "The capacity of cooling ponds to dissipate heat", Proc. Amer. Power Conf. 33, 446 (1971).

PA-227 Palmer-Hostik & Assoc., Private communication, Houston, Texas, 2 August 1976.

PE-161 PEDCo-Environmental Specialists, Inc., Summary Report-Flue Gas Desulfurization Systems - April 1975. EPA Contract No. 68-02-1321, Task No. 6, Cincinnati, Ohio, 1975.

PE-R-277 Perry, John H., Chemical engineers handbook, 5th edition, New York, McGraw-Hill, 1973.

RE-211 Resources Conservation Co., Feasibility study for Arizona Public Service Company Four Corners power station. Renton, Washington, April 13, 1976.

RO-266 Rogers, A. N. and L. Awerbuch, "Reuse or disposal of salts from power and desalination plant wastes", in Proceedings of the 3rd National Conference on Complete Water Reuse: Symbiosis as a Means of Abatement for Multi-Media Pollution, Cincinnati, June 1976, Lawrence K. Cecil, ed., N.Y., AIChE, 1976.

TH-192 Thompson C. G. and G. A. Mooney, Recovery of lime and magnesium in potable water treatment. EPA 600/2-76-285, Montgomery, Alabama, Black, Crow, and Eisdness, Inc., December 1976.

UH-007 Uhlig, Herbert H., Corrosion and corrosion control, an introduction to corrosion science and engineering. N.Y., Wiley, 1963.